PAINT BLOCKING IN FORD'S IN-LINE VEHICLE SEQUENCING ENVIRONMENT

by

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B.S., Computer Engineering
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Submitted to the Sloan School of Management and the
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ABSTRACT

In-Line Vehicle Sequencing (ILVS) is a new manufacturing paradigm that promises to fundamentally change the way Ford builds its vehicles. ILVS leads to reduced inventory and floor space requirements as well as to improvements in productivity and quality, thereby reducing costs for the entire manufacturing system. Block Painting – the concept of painting cars in batches of like-color – also represents a huge potential savings. While both initiatives are very important, they run the risk of conflicting with each other.

Using discrete-event simulation, this thesis first evaluates the conventional approach to Block Painting, determining that it is incapable of meeting stated ILVS and Block Painting objectives (i.e., block sizes in the range of 3 to 5). The thesis then proposes an approach to ILVS that could enable the formation of unexpectedly large paint blocks without compromising the system's ability to maintain sequence. This approach, known as 'pre-sequencing', involves the pre-scheduling of vehicles to accommodate predictable downstream disruption. The thesis also shows that the new approach can lead to significant improvements in automobile sequencing.

Specifically, the conventional approach increases the average block size for the Wixom assembly plant from 1.2 to 2.1 (corresponding to an annual savings of approximately $1,000,000) without significantly disturbing sequence control. The pre-sequencing method further increases the average block size to 3.6 – for an additional $700,000 in annual savings – while equivalently (minimally) disrupting sequence control. When used exclusively to improve sequence control capabilities, the pre-sequencing concept is capable of reducing the size of the re-sequencing bank (the AS/RS) by at least 5%.

The conventional approach, while economical to implement, is highly dependent on the number of distinct body-in-white configurations in the system. For most assembly plants, this dependency renders the approach ineffectual. Wixom is somewhat of an exception due to its low complexity level. The pre-sequencing method, in contrast, is completely independent of the body-in-white complexity. Thus, its Block Painting performance remains stable regardless of the context. For both Block Painting methods, the thesis stresses the importance of implementing block protection – the concept of preventing repaired vehicles from breaking paint blocks as they re-enter the build sequence. Without it, the average block size generated by pre-sequencing degrades from 3.6 to 2.7.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

THESIS INTRODUCTION

1.1 Introduction

Henry Ford, in 1913, revolutionized the automobile industry when he introduced the moving assembly line. To manufacture his Model T he used a paced assembly line equipped with conveyor belts to bring parts directly from machine tools to the assembly areas and then to move the sub-assemblies along the production line. A dedicated assembly line produced each major section of the Model T – the engine, chassis, and body – that the system subsequently brought together. This innovative approach to manufacturing greatly improved material handling and led to significant increases in productivity. Ford's insistence on total vertical integration minimized supply-chain coordination issues, while his effort to standardize product offerings kept complexity and costs low.

Modern automobile production is an elaborate process involving the assembly of more than 15,000 individual parts [4]. A strong customer focus has prompted companies to offer a huge number of options, accessories, and colors for each vehicle model. The result of such immense product complexity is high demand uncertainty and schedule instability. In response to customer requirements, manufacturers have also modified their production practices to provide higher quality vehicles within shorter lead times and at lower cost. Lean production and agile manufacturing principles, such as just-in-time (JIT) inventory management and sequenced part delivery (SPD), have been at the heart of this effort.

The assembly line, in its traditional form, has been unable to keep pace with these trends. The proliferation of product configurations has undermined the use of conventional scheduling algorithms for manual assembly lines. Moreover, the inability of upstream body and paint processes to preserve vehicle sequence has exacerbated the scheduling problem while thwarting efforts to reduce inventory. In recent years, however, researchers and practitioners have developed a number of new approaches for improved planning and scheduling as well as coordinated multi-stage manufacturing operations.

Advances in the areas of planning and scheduling include new mixed-model scheduling algorithms, complexity reduction techniques, and simulation modeling tools. The literature has devoted much attention to increasing the utilization of workstations in manual assembly lines, whose cycle times depend heavily on customer-selected options. Earlier research has focused both on balancing assembly lines to accommodate an "average" mix of options, and on determining the appropriate input sequence to assembly lines in order to smooth out the flow of work [1]. As the number of vehicle options continues to increase, however, researchers are seeking new ways to strategically schedule the proliferated product lines. Rachamadugu and Yano [9], for example, compute a criticality index for each workstation, to quickly identify which stations to include in assembly line sequencing algorithms.

Reducing the complexity of the product structure is also essential for promoting schedule stability. Ford and General Motors are determined to reduce complexity, while providing for customer needs, through better engineering, marketing, and merchandising [3]. Likewise, Toyota, for one of its new sport-utility vehicles, has reportedly pushed much of the build complexity out of the assembly plants by bundling many of the vehicle options into dealer-installed packages [5].

Another trend that is likely to improve planning and scheduling capabilities is the extensive use of computer simulation in designing plants and determining major operation parameters. Simulation models enable plant personnel to examine and test alternatives, analyze the effect of changes in product mix, and forecast the performance of the system. In some cases, simulation modeling can even provide for real-time scheduling of automation equipment [10]. New color animation tools, combined with friendlier user interfaces, are encouraging the widespread use of analytical simulation languages [7].

The automobile industry has also recognized the central importance of well-coordinated operations to help stabilize scheduling. One of the thrusts in the industry's attempt to re-think the traditional assembly line has been to replace people with automation, since robots can consistently perform repetitive tasks without becoming bored [2]. The adoption of new technology has reduced variability in, and improved the operations of, certain areas of the assembly plant. Experience has shown, however, that people are still indispensable for most assembly operations. Thus, another thrust has been to adjust the system to better fit the characteristics of human operators. Buzacott [2] examines the possibility of allowing operators to control the release of work from their stations to avoid the propagation of defects into the system. He also proposes that an assembly system should organize workstations into a parallel structure with more tasks assigned to each cell. While the Audi body assembly plant in Ingolstadt, West Germany has demonstrated the positive effect of group assembly on quality [8], Bolat [1] highlights the potential pitfalls of such paradigms, stessing that "efficient utilization of the existing systems is still needed."

Perhaps the most notable advances in assembly plant operations have come in the form of streamlined material management processes and electronic vehicle-tracking systems. In order to provide the customer with "the right products, delivered on time, in the correct amounts, and with the highest degree of quality", the industry has developed new materials management techniques [10]. Innovations include automatic-guided vehicle (AGV) systems, the automated storage and retrieval system (AS/RS), and a variety of other material handling systems designed for flexibility. The addition of automated vehicle tracking and scheduling promises to achieve the fully automated "factory of the future" [6]. By combining such sophisticated systems with conventional buffers, banks, and loops, automobile manufacturers are learning how to maintain sequence in the build process. This effort has been able to reduce inventory and improve the stability of schedules.

1.2 Problem Statement

Ever since the introduction of the moving assembly line, automobile manufacturing has been based on the concept of maintaining job sequence throughout the entire assembly process. For several reasons, including randomness in the painting process and the off-line repair of defects, this goal has been difficult to achieve. To remedy this situation, Ford has begun implementation of In-Line Vehicle Sequencing (ILVS) – a new manufacturing paradigm that promises to fundamentally change the way Ford builds its vehicles. This approach to factory operations seeks to stabilize manufacturing schedules by maintaining a set vehicle sequence in the automotive assembly plant. ILVS thus enables suppliers to manufacture and deliver components in sequence, leading to reduced inventory and floor space requirements as well as to improvements in productivity and quality, thereby reducing costs for the entire manufacturing system.

Block Painting – the concept of painting cars in batches of like colors – also can create a huge economic savings. Whenever a vehicle body requiring a different color enters the enamel booth, the automation equipment must remove the previous paint color before loading the new paint color. Each paint purge incurs significant costs in paint and solvent usage. Consequently, reducing the number of paint purges, due to color changes, significantly reduces the use of expensive bulk material.

Ford has designated both In-Line Vehicle Sequencing and Block Painting as operating imperatives that are scheduled for accelerated global system roll-outs. While both initiatives are very important, they potentially could conflict with each other. ILVS aims to maintain vehicle sequence throughout the build process, while Block Painting, as most plan to implement it, acts to disrupt sequence.

1.3 Goals and Objectives

The primary objective of this thesis is to demonstrate that In-Line Vehicle Sequencing and Block Painting can harmoniously coexist. This research presents and analyzes a new approach to the problem, that optimizes the key performance criteria by accommodating all foreseeable disruptions, including Block Painting, in the initial vehicle sequence. Our approach uses discrete-event simulation to evaluate the new method and to compare its performance to competing approaches. We use the insights gained from the simulation model to improve the performance of the system. Although much of the discussion and all of the recommendations pertain specifically to Ford, the results in this thesis might be useful in other contexts for improving scheduling and sequence control in staged production processes.

1.4 Overview of the Remaining Chapters

Chapter 2 reviews the vehicle scheduling and assembly process in use by most of Ford's assembly plants. To understand the benefit of In-Line Vehicle Sequencing and the way it enables Block Painting, we must first gain some insight into the conventional way of building cars. This chapter then introduces the concepts of In-Line Vehicle Sequencing and Block Painting.

Chapter 3 discusses alternative approaches to combining ILVS and Block Painting. Several criteria contribute to the desirability of a Block Painting method. This chapter explains why the commonly accepted technique, when implemented in an ILVS context, fails to achieve many of the desired goals of Block Painting. It then presents a new approach to the problem that might improve not only Block Painting, but also ILVS in general.

Chapter 4 calculates the purge costs needed to evaluate the effectiveness of Block Painting. The commonly used metric, average block size, measures only the quantity of material wasted by color changeovers in the painting process. The analysis in this chapter shows that some colors are considerably more expensive to purge than others. Therefore, we require a new Block Painting metric – one that accounts for the cost of purging – to better assess the total cost of wasted paint material.

Chapter 5 simulates the various approaches to Block Painting in the ILVS environment. It starts by explaining the need for a simulation model, and then presents the simulation data. The chapter then shows how the conventional and proposed Block Painting approaches compare to the base case of ILVS without Block Painting. The simulation results suggest that the conventional approach might lead to modest improvements in annual purge costs for plants with low vehicle complexity, while the proposed approach should lead to considerably larger reductions regardless of vehicle complexity.

Chapter 6 shows how to use pre-sequencing – the core mechanism of our new approach to Block Painting – to improve ILVS sequence control capabilities. It first explains the underlying theory, and then uses the simulation model of Chapter 5 to establish its validity. The findings presented in this chapter highlight the untapped potential of opportunistic scheduling in the ILVS system.

Chapter 7 addresses the implementation requirements in two ILVS contexts. The ideal ILVS environment requires only minor programmatic changes to the factory scheduling and control systems. The practical ILVS environment, on the other hand, requires hardware modification as well. This chapter considers a strategy for implementing the necessary changes.

Chapter 8 summarizes the research and recommendations presented in this thesis and suggests some related topics for further investigation.

Chapter 2

BACKGROUND ON FORD'S VEHICLE SCHEDULING AND ASSEMBLY PROCESS

In the US auto industry, each company determines its production schedule differently. Both General Motors and Chrysler, for example, create sales forecasts based on a variety of factors, including capacity considerations and vehicle sales. They then match sales orders to their forecasts to arrive at specific build sequences. While GM matches sales orders to its forecast on a rough model-for-model basis, Chrysler creates a build sequence that is identical to its forecast. Ford, on the other hand, bases its build sequence directly on sales orders that are "organized according to a national blend of models that can be digested by the plant" [6].

This chapter provides a brief overview of Ford's vehicle scheduling and assembly practices. First, it highlights some of the issues surrounding sequencing and schedule stability that Ford, along with the rest of the automobile industry, has traditionally endured. It then describes Ford's In-Line Vehicle Sequencing (ILVS) system – a new manufacturing paradigm that could remedy some of the prevailing problems. Finally, the chapter introduces the concept of Block Painting. This initiative, while of great economic interest to the company, could detract from the success of ILVS.

2.1 Conventional Vehicle Scheduling and Assembly

The typical domestic automotive assembly plant consists of a body shop, a paint shop, a trim shop, a chassis shop and a pre-delivery area. The body shop welds sheet metal together in a highly automated process to form an unpainted vehicle body, or body-in-white. The paint shop adds corrosion protection and a colored enamel coating to the body-in-white. These operations are highly automated. In contrast, the trim and chassis shops, known in aggregate as the final assembly area, rely largely on manual labor. The trim shop primarily installs the interior of the car, while the chassis shop adds the power-train, suspension, wheels, etc. The pre-delivery area supports final vehicle inspection and any minor repairs and adjustments needed before the cars are ready to ship [11].

In spite of their mechanized environments, the paint and body shops suffer from significant sequence distortion. Although a variety of off-line repair areas in both shops are contributing factors, the most dramatic disruption to the sequence occurs when a vehicle has to be repainted. As a result, vehicles arrive at the final assembly area in essentially random order. A pre-ILVS study of Ford's Wixom assembly plant examined the arrival pattern of 500 vehicles to the final assembly area. This study revealed that cars reached the trim shop from 300 jobs early to 4500 jobs late, with a standard deviation of 1250 jobs (approximately 25 hours worth of production) [26].

All vehicles are built to order. When the central scheduling office receives orders from district sales offices, it creates twelve-day order banks for the assembly plants. Each assembly plant decomposes its order bank into weekly and daily schedules, or buckets. These schedules must first cater to fixed capacity limitations and to raw material availability. They next give priority to the balancing of option content to properly utilize manual labor in the trim shop. Finally, the schedule can address the body and paint shop priorities. As soon as the assembly plants establish buildable schedules, they relay the daily buckets to their suppliers by way of the scheduling office [11].

Demand instability typically adds considerable complexity to the running of a plant, especially to capacity planning and the sourcing of raw materials. Instability in the sequence of vehicles arriving from body and paint makes matters even worse. These effects impact the suppliers of the assembly plant as well. Suppliers are forced to deliver a wide range of products to the assembly plant, leading to high inventory levels, to cover the spread of vehicles arriving at trim. To balance option content at the trim and chassis shops, using a painted-body bank to establish a nine or ten car rotation is usually the best that can be done. This is far from optimal. Having a predictable sequence could help minimize inventory, eliminate labor, and increase quality. Also, firming up the schedule in advance would enable suppliers to plan better and save money.

2.2 In-Line Vehicle Sequencing

Several approaches exist for improving sequence control in the assembly plant. To the extent possible, automobile makers can remove the sources of sequence disruption – which are typically facility related, process related, or operating practice related [22]. Alternatively, assembly plants can install small delay buffers to recapture local disruptions, or large sortation buffers to re-sequence longer segments of the vehicle stream.

Ford's In-Line Vehicle Sequencing initiative combines each of these approaches with advancements in vehicle tracking and material handling for a highly robust solution to the problem. ILVS promises to integrate the body and paint areas, the final assembly lines, and the suppliers of an automotive assembly plant into a single cohesive manufacturing entity. ILVS uses a combination of computer technology and process discipline to maintain sequence in the body and paint areas and thus enables the plant to introduce the same vehicle sequence into final assembly as the one established in the schedule a minimum of five days in advance. This sequence represents the order in which the trim and chassis areas would like to see the painted car bodies arrive. A well-chosen sequence would not only help balance the line-load requirements so that workers would be neither over- nor under-utilized, but would also allow selected suppliers to manufacture and deliver material in a just-in-time fashion and in vehicle sequence to the point of use. Obviously, this ability would drastically reduce the need for the trim and chassis areas to maintain large supply inventories. Figure 2-1 shows the basic ILVS structure.

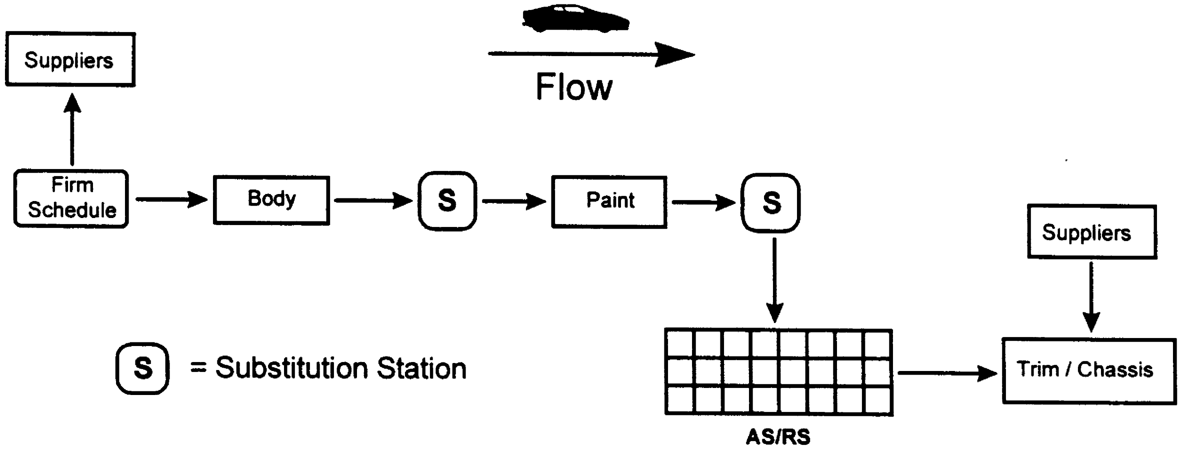


Figure 2-1: The basic ILVS structure

ILVS is necessary because the vehicle build sequence becomes disrupted at several locations between the entrance to the body shop and the exit of the paint shop. As vehicles pass through the body and paint areas, several factors including varying processing requirements, capacity constraints, and conveyor routing lead to disruptions in the sequence order. These disruptions can be broadly classified as controllable and uncontrollable. An example of a controllable disruption in the paint shop is two-tone painting. This process is guaranteed to disrupt the sequence since each two-toned vehicle passes the paint booth at least twice, while monotone vehicles normally pass through only once. Uncontrollable disruptions in the body and paint shops are primarily associated with rework. Depending on the severity of the needed rework, uncontrollable disruptions might be further classified as major or minor. In the paint shop, for example, major rework would necessitate an additional loop through the paint operation, while minor rework would call only for some spot repair. ILVS acts to counteract the effect of each of these disruptions to restore the original build sequence.

ILVS employs several methods for accomplishing these goals. First, it eliminates many of the sources of disruption that were previously uncontrolled. In Ford's Wixom assembly plant, for instance, a consulting company working with Ford identified over sixty sources of disruption, and eliminated the ones resulting from outdated practices (see Section 5.1.3). This left only a few easily identifiable sources of uncontrollable disruption, making the problem much easier to understand.

The Automated Vehicle Scheduling and Automated Vehicle Identification (AVS/AVI) system is the primary enabler of ILVS. This system, made up of a centralized database, mobile transponders, stationary readers, and sophisticated conveyors, permits vehicle tracking and in-line vehicle substitution. The latter is a method which alters the sequence of vehicles by changing their identification numbers rather than physically switching their location. Several substitution points (indicated in Figure 2-1 as rounded 'S' boxes) exist before and after the paint shop. When a body-in-white (BIW) passes one of these points after the body shop, or a painted body passes such a point after the paint shop, the system examines its sequence number. If another entity of exactly the same configuration exists upstream and its sequence number is lower than the one being examined, then the two entities are swapped in the database. This action provides a re-sequencing effect.

The plant's level of vehicle complexity directly influences the strength of the substitution effect. We can define vehicle complexity as the number of unique vehicle types that can appear at a specific point in the production process. The greater the number of unique configurations, the poorer the possibility of having two like-entities to substitute. Figure 2-2 portrays the concept of substitution for a vehicle sequence with a complexity level of two. Generally, before a plant can embrace ILVS, it must launch a campaign to dramatically reduce these complexity levels.

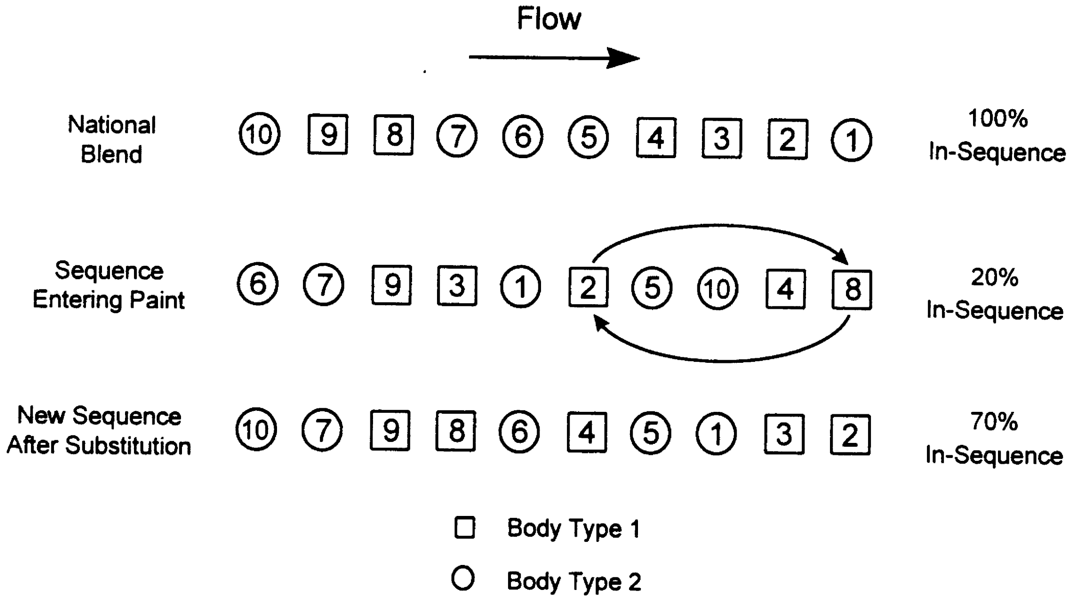


Figure 2-2: The concept of substitution (adapted from [20])

The other major mechanism that ILVS uses to restore sequence is the Automated Storage and Retrieval System (AS/RS). This completely automated and randomly accessible unit sits near the paint shop and can hold several hundred car bodies. The AS/RS is not intended to function as an inventory store of every combination drawn out for final assembly (and later replaced from body/paint), nor as a buffer of completed work to protect against down time. Rather, the AS/RS functions as a re-sequencing facility that holds painted bodies arriving early and provides time for late units to re-enter the sequence. The spread of vehicles out of sequence is the primary driver in sizing the AS/RS re-sequencing bank. Figure 2-3 shows the AS/RS in use at the Wixom assembly plant.

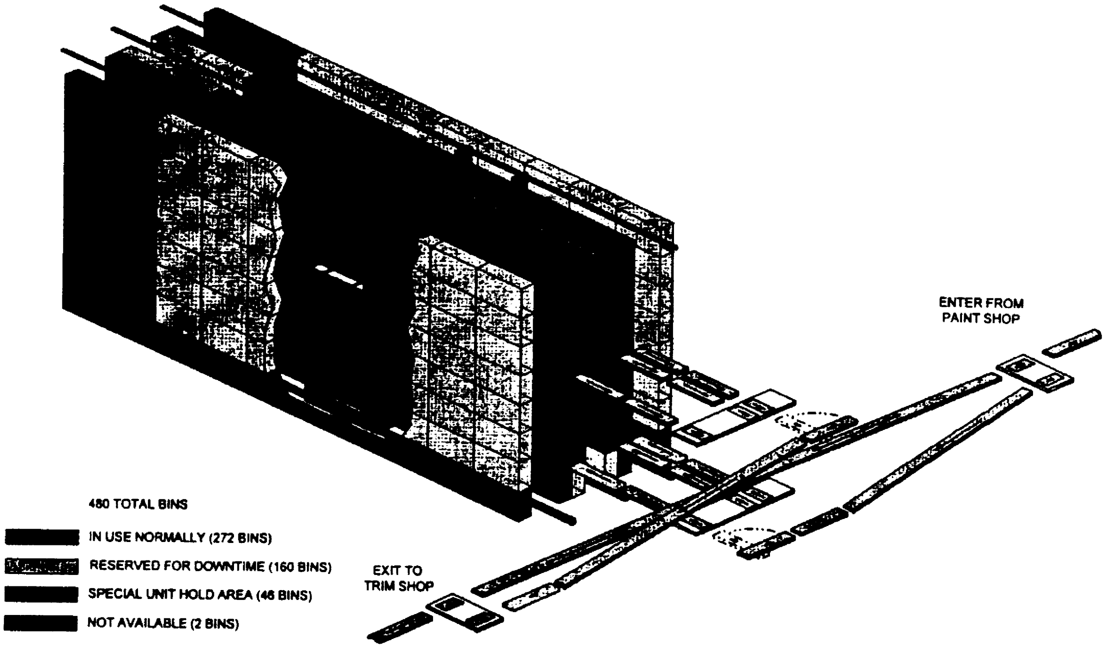


Figure 2-3: The Wixom AS/RS [21]

Ideally, In-Line Vehicle Sequencing would be capable of maintaining perfect sequence. However, the plant could achieve this objective only at unacceptably high cost. Instead, Ford insists that no less than ninety-eight percent of the vehicles arrive to trim in sequence – an affordable goal which achieves most of the potential benefits of perfect sequence control [22].

2.3 Block Painting

Whenever a body-in-white requiring a new paint color enters the paint booth, the system must purge the previous paint from the application equipment before it can load the new paint. These purges waste significant amounts of paint and solvent material. Ford wishes to implement Block Painting measures not only for the obvious financial savings, but also for the positive environmental impact resulting from reduced paint and solvent usage.

Figure 2-4 demonstrates the impact of paint block size on paint and solvent usage. Increasing the number of vehicles entering the enamel booth in blocks of like color directly reduces the number of purges. Notice that we realize most of the potential material savings as the average block size expands from one to three.

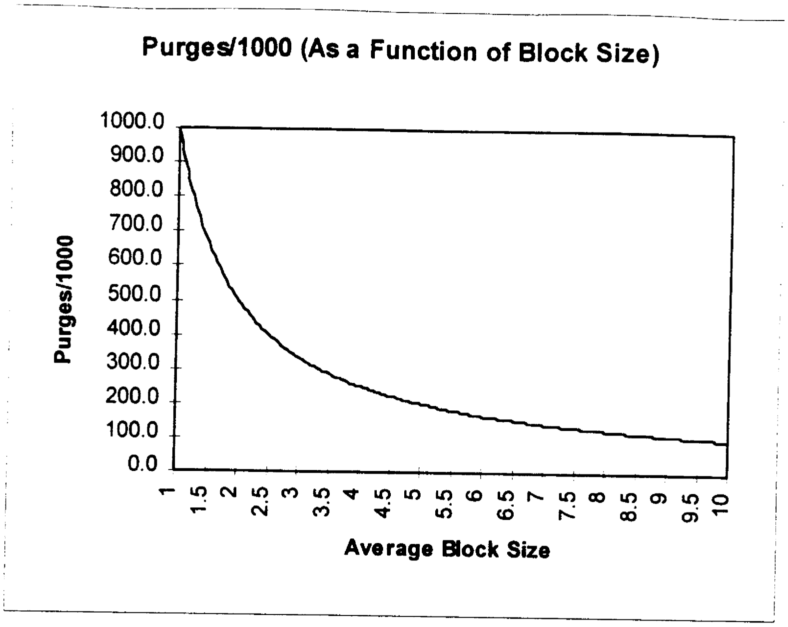


Figure 2-4: The relationship between average block size and the quantity of wasted paint and solvent material

Figure 2-5 translates these material savings into annual monetary savings for a typical plant. Assuming a cost per paint purge of ten dollars (an actual purge ranges from five dollars to thirty dollars and depends on the spray equipment and the type of paint used) and a production volume of 200,000 vehicles per year, the incremental savings are dramatic as the average block size increases from one to three, less pronounced from three to five, and small past five. Chapter 4 presents normalized purge costs for Ford's Wixom assembly plant.

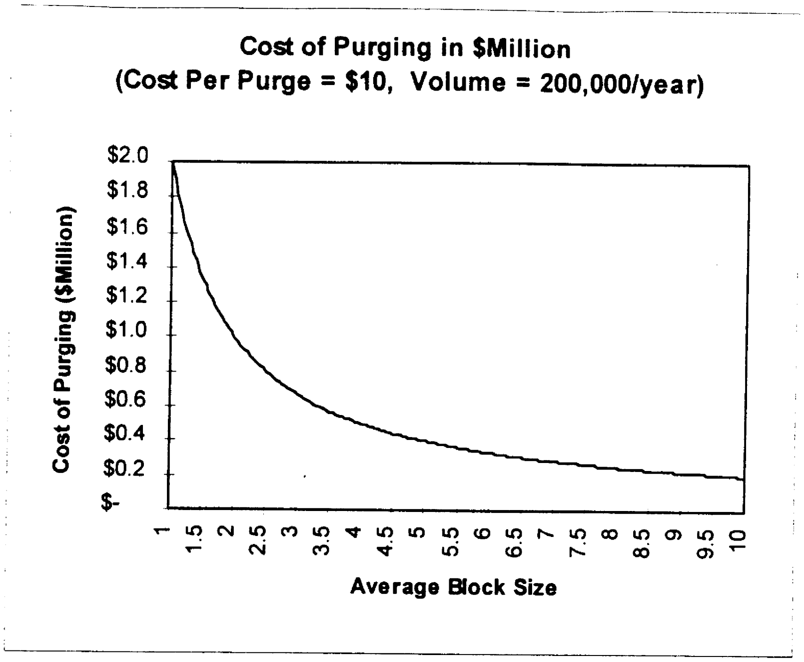


Figure 2-5: The relationship between average block size and the cost of wasted paint and solvent material

An obvious solution to the Block Painting problem comes to mind right away. Why not simply organize the incoming sequence (known as the National Blend) into streams of like paint colors arranged in very large blocks? This certainly is a logical approach, but its applicability is limited. The algorithm that establishes the National Blend sequence accounts for a variety of assembly plant constraints, each of different priority. In fact, the formation of paint blocks is one of these constraints. However, other requirements, such as labor balancing, have higher priorities and thus take precedence. For this reason, sorting the cars according to paint color, for the purpose of forming paint blocks, is not likely to occur to any significant degree. Therefore, the system must accomplish paint blocking through other methods. The conventional approach attempts to form paint blocks by a using the AVS/AVI system to swap or substitute Vehicle Identification Numbers (VIN) and target paint colors.

In non-ILVS environments (which most plants still are), the addition of AVS/AVI infrastructures could accommodate this methodology. However, many of the changes that need to be made are the same as those required by an ILVS implementation. One might therefore conclude that Block Painting should be accommodated easily when ILVS is finally implemented, since Block Painting depends on the same technology and infrastructure as ILVS. Simulation studies and actual experimentation have shown, however, that this approach will work only if a plant reduces its body-in-white complexity to a bare minimum (for reasons explained previously) [24, 25]. This study evaluates the possibility of using substitution for Block Painting in the Wixom environment and also explores an alternative approach to Block Painting.

Chapter 3

INTEGRATION OF IN-LINE VEHICLE SEQUENCING AND BLOCK PAINTING

3.1 Conventional Approach

Sequence control is the primary objective of ILVS. When considering the prospect of paint blocking in such an environment, we cannot compromise the system's ability to deliver vehicles in sequence to the final assembly area. In addition, the vehicles must somehow reach the enamel booth in reasonably large batches of like color. If this were not the case, the paint blocking effort would be useless. Beyond these two prerequisites, a desirable implementation neither requires extensive hardware modification nor results in significant increase in the time a vehicle spends in the build process.

In response to these criteria, the conventional approach to combining paint blocking with ILVS involves a simple modification to the algorithm used by the substitution station just prior to the enamel booth. Recall from Chapter 2 that in an ILVS system without paint blocking, this substitution station reduces the spread of vehicles out-of-sequence by assigning each vehicle that passes by the substitution station the lowest sequence number of all the upstream vehicles that have the same body configuration. To achieve paint blocking, we adjust the algorithm to build 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 that is within a given search window of the one with the absolute lowest sequence number. For example, a blue car arrives at the substitution station. Because a green car preceded it, we would like to paint another green one. The reader device at the substitution station reports to the AVS/AVI system that the current car is of body configuration X. The system recognizes that of all the cars of configuration X yet to reach the substitution station, the one with the lowest sequence number is Y. Normally, the AVS/AVI system assigns this sequence number to the car at the substitution station. In this case, however, if a green upstream vehicle of type X lies within a designated search distance (say 50 cars) from the lowest one, Y, then the system would assign its sequence number to the current car. This substitution action results in a block of two green cars; however, it also imposes an additional distortion to the sequence, in proportion to the size of the search window used. Figure 3-1 shows substitution being used to create paint blocks of size three.

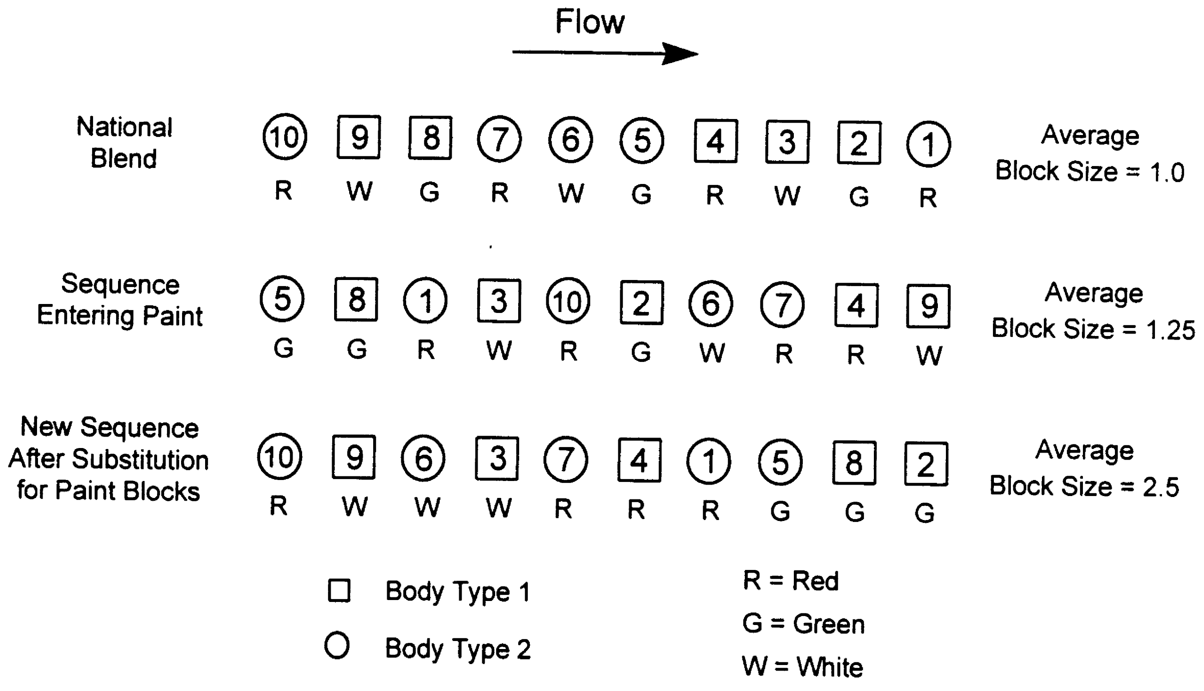


Figure 3-1: A representation of Block Painting by substitution

This scheme satisfies the criteria for a desirable block painting method by avoiding hardware additions or the alteration of vehicle flow. However, because the substitution effect hinges directly on the level of BIW complexity (the number of distinct body-in-white configurations), the ability to achieve adequate block sizes without seriously degrading sequence control is questionable. Chapter 5 shows that this conventional approach performs rather poorly in terms of both block creation and sequence control. For this reason, we search for an alternative approach.

3.2 Proposed Approach

In an ILVS assembly plant, the sequence entering the body shop is the same as the sequence expected in final assembly. Conventional wisdom dictates that the surest way to end up with a certain sequence is to start with that sequence and then protect against or reverse the effect of each disruption along the way. We might amend this current practice for two reasons. First, while the National Blend is geared for minimizing inventory and balancing work-load, it is not necessarily optimized for sequence control. That is, some variation of the sequence might be preferable, giving a higher probability that the National Blend will reach the final assembly area in sequence. Second, the National Blend doesn't really attempt to facilitate Block Painting. If the National Blend were actually to contain some paint blocks then the sequence would be "paint-shop friendly" (i.e., by accounting for paint shop needs). Keep in mind that this is no oversight on the part of the scheduling department, but rather a limitation. Given that the National Blend scheduling algorithm must satisfy many other constraints in final assembly, embedding paint blocks into the blend is extremely difficult.

The AS/RS, which sits between the paint/body and trim/chassis areas of the plant, might offer a solution. As a completely random-access buffer, the AS/RS acts to de-couple these major sections of the facility; thus, it could allow for both a friendly sequence for the trim and chassis shops as well as a modified sequence for the body and paint shops. The modified sequence would not only shuffle the National Blend sequence to form large paint blocks, but would also deal with those vehicles believed to cause disruption. *The central concept of this thesis is that the initial vehicle sequence should, as much as possible, accommodate all foreseeable disruptions, including Block Painting.* The system should use dynamic sequence control capabilities (i.e., substitution, delay buffers, etc.) only for the unpredictable disruptions. Since Block Painting is known to cause disruption (i.e., to cause cars to become out of sequence), the system could deal with Block Painting ahead of time by forming the blocks in the sequence, rather than using on-the-fly substitution.

The idea underlying this approach is simple and could potentially add considerable flexibility to ILVS. The system should deal with anything predicted to cause a disruption in the body or paint shops ahead of time. For example, the system could schedule two-toned vehicles, which are guaranteed to become out of sequence and be delayed, earlier in the new body shop sequence. Although this type of scheduling could potentially correct for all controllable and predictable disruptions, the biggest beneficiary of such flexibility is likely to be Block Painting.

As our analysis will show that, regardless of the BIW complexity, we can group together large paint blocks from the National Blend sequence without dramatically disturbing it. We will also demonstrate, in the chapters that follow, that if we introduce this new blocked sequence into the body shop, reasonably large paint blocks will arrive at the paint booth. The process discipline and computer capabilities advanced by ILVS enable a plant to maintain sequence much better than previously possible without ILVS. Finally, we will show that the ILVS system is able to restore the National Blend sequence by utilizing the last substitution station (the one after paint) and the AS/RS facility, so that the arriving trim sequence will conform to acceptable ILVS sequence metrics.

The rest of this chapter describes the basic methodology for creating and protecting the modified sequence. It presents two ILVS environments that could benefit from the pre-sequencing methodology: (i) an environment that strictly adheres to In-Line Vehicle Sequencing guidelines and (ii) the Wixom assembly plant – Ford's only North American ILVS installation. While Wixom has done an admirable job of making ILVS a success, some areas of the plant deviate from certain underlying conventions of In-Line Vehicle Sequencing.

3.2.1 Needs Versus Requirements

Before delving into the specifics of implementation, let us first differentiate between the requirements, or constraints, of an assembly plant, and the plant's needs. At Wixom, for example, every fourth car released into the main body shop must be a small car. It is important to understand that, barring a major change in operating policy, this is a non-negotiable constraint. A need, on the other hand, is something that would be nice to have, but either would be in conflict with the existing system, or would be impractical to implement given current practice. Block Painting is a prime example of a paint shop need. It certainly would be desirable for cars to arrive at the enamel booth in blocks of like colors, but given the current system configuration, this objective would be difficult to accomplish. Also, if implemented without appropriate adjustments to the system, Block Painting would conflict with the current sequence control capabilities.

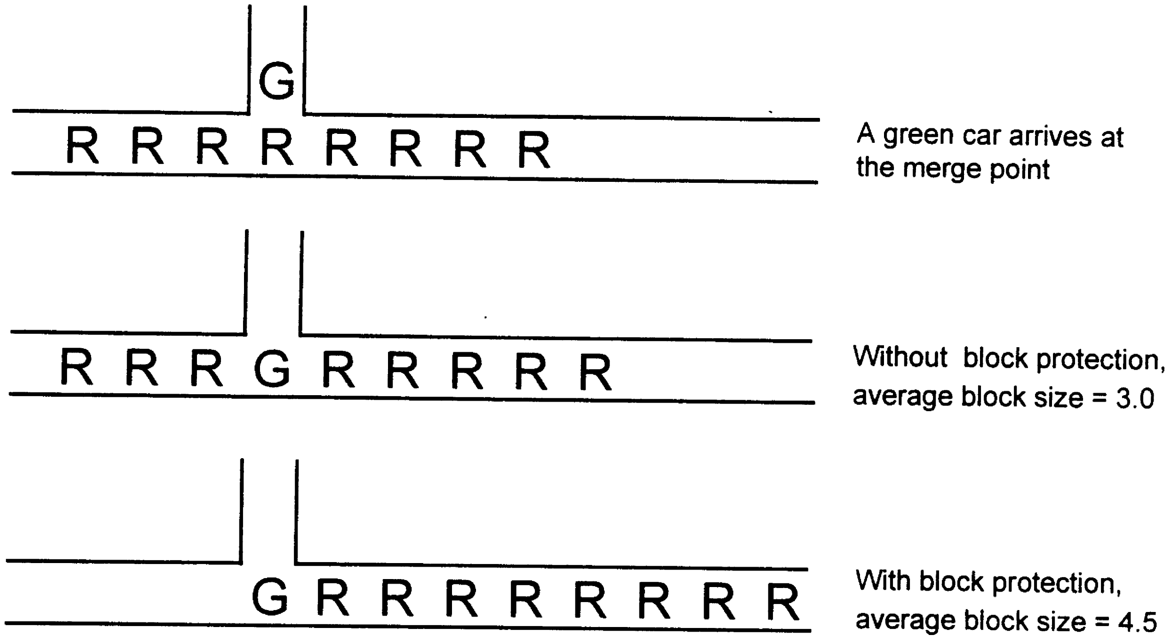
3.2.2 Pre-sequencing

Paint blocks occur in the National Blend mostly by chance. For example, in a blend containing a uniform distribution of fifteen colors, the expected block size is 1.07. The fact that some colors occur more frequently than others tends to raise this average slightly. Moreover, because paint blocking is one of the optimization criteria in the National Blend scheduling algorithm – albeit a relatively weak one – this average creeps up a little more. Even with these exceptions, the average block size in the National Blend rarely exceeds 1.2. Pre-sequencing attempts to create a modified National Blend sequence containing much larger blocks.

The ability to form blocks from the National Blend, before it is introduced into the system, depends only on the frequency distribution of paint colors. Compare this with the method of creating blocks through substitution. The success of this latter method depends heavily on the probability distribution of body-in-white configurations in addition to the frequency distribution of paint colors. Appendix A specifies the pre-sequencing algorithm.

3.2.3 Block Protection

The block protection mechanism we propose for use with Block Painting is surprisingly simple. The concept of protection introduces a safeguard on streams of like-colored vehicles (i.e., paint blocks) by having the system maintain the integrity of the paint blocks until they can reach the enamel booth. Each time the system pulls a vehicle off for repair and later re-introduces it into the flow, the effect on Block Painting is very undesirable. Removing the vehicle from the original stream, reduces the size (by one car) of the block that contained it. Furthermore, when the vehicle re-enters the stream, it is unlikely to join a block of its own color. Thus, it forms a new block of size one and thus introduces a paint purge all by itself. Even worse, this 'one-er' is likely to break up a perfectly good block. If a block of eight like-colored vehicles were flowing by when a lone vehicle enters the stream, the introduction of this vehicle would break up the large block into two smaller blocks (of size six and two, five and three, four and four, etc.). The result is equivalent to an average block size of 3.0. If, on the other hand, the 'one-er' could wait until the block of eight passes by, the resulting block configuration would be a block of eight and then a block of one, corresponding to an average block size of 4.5. Figure 3-2 illustrates this example. The difference between having and not having this sort of block protection can be very significant.



A green car arrives at the merge point

Without block protection, average block size = 3.0

With block protection, average block size = 4.5

Figure 3-2: The concept of block protection

3.2.4 Ideal Implementation

The ideal implementation assumes that, by design, the National Blend meets the requirements of only the trim and chassis areas of the plant. Therefore, the body and paint shops impose no constraints on the sequence of vehicles passing through them. Thus, we are free to design an entirely new sequence for the paint and body shops as long as we can restore it to the National Blend sequence before the final assembly area. Given this situation, the pre-sequencing methodology attempts to meet the needs of the paint shop through a modified blend sequence, and relies on the AS/RS to revert to the original blend sequence (the National Blend).

The ideal implementation also assumes that the paint shop consists of just one paint booth and that the factory builds to only one National Blend. Of course, this idealized model also relies on the sequence being rigorously maintained throughout the system. For example, ILVS guidelines specify that the vehicle flow through parallel processes must not contribute to sequence disruption. As such, parallel processes must be identical in terms of processing time and must allow for vehicles to enter and exit them in a consistent, alternating fashion. In practice, a plant will violate each of these assumptions to one degree or another. The generalized approach, however, serves to demonstrate not only the concepts of pre-sequencing and block protection, but also what can be expected from a system designed with these concepts in mind.

Given these assumptions, the mechanisms set forth by ILVS, and the concepts of pre-sequencing and block protection, Block Painting naturally follows. Figure 3-3 shows the steps involved in pre-sequencing and National Blend restoration. Chapter 5 simulates this ideal implementation with real data to prove the validity of the underlying approach.

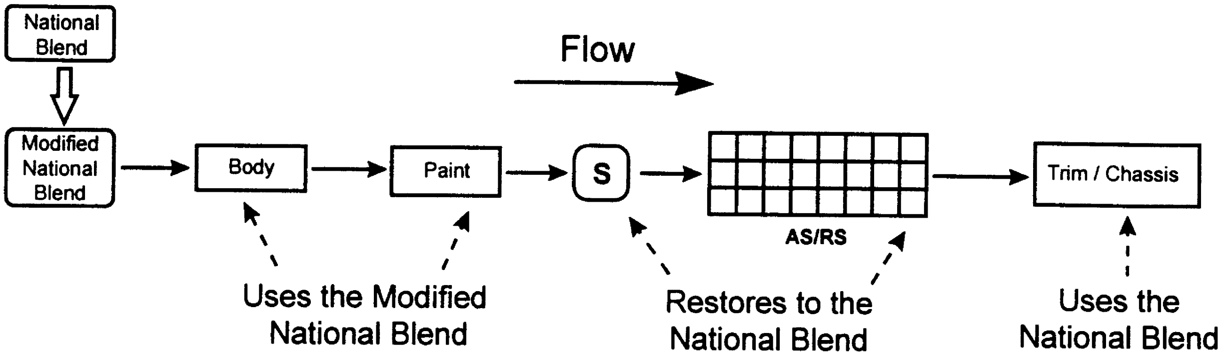


Figure 3-3: The concept of pre-sequencing (modification and subsequent restoration of the National Blend sequence)

3.2.5 Wixom-Specific Implementation

Wixom is the home of Ford's Lincoln luxury car division, which produces the Town Car, Continental and Mark VIII. The Town Car, Lincoln's flagship product, is produced in the largest quantity. Wixom commonly refers to the Town Car as the big car and to the Continental and Mark VIII as small cars. The plant produces the Town Cars, Continentals, and Mark VIIIs in the ratio 6:2:1. It builds the Town Car and Continental bodies-in-white in the main body shop and the Mark VIII bodies in a separate body shop. It had been theorized that, because of the Mark VIII's significantly lower volume, the reduced line rates realizable in dedicated facilities would result in product of higher quality.

Figure 3-4 summarizes the flow of vehicles through the Wixom assembly plant. The Wixom assembly process contains a relatively high degree of surge and in-process vehicle flow time since it produces three distinct car lines, none of which share the same chassis. The other exception specific to Wixom involves its dependence on a strict rotation between its large and small cars. Specifically, the Town Car/Continental National Blend is organized so that a single Continental succeeds every three Town Cars. This concept is used throughout the plant.

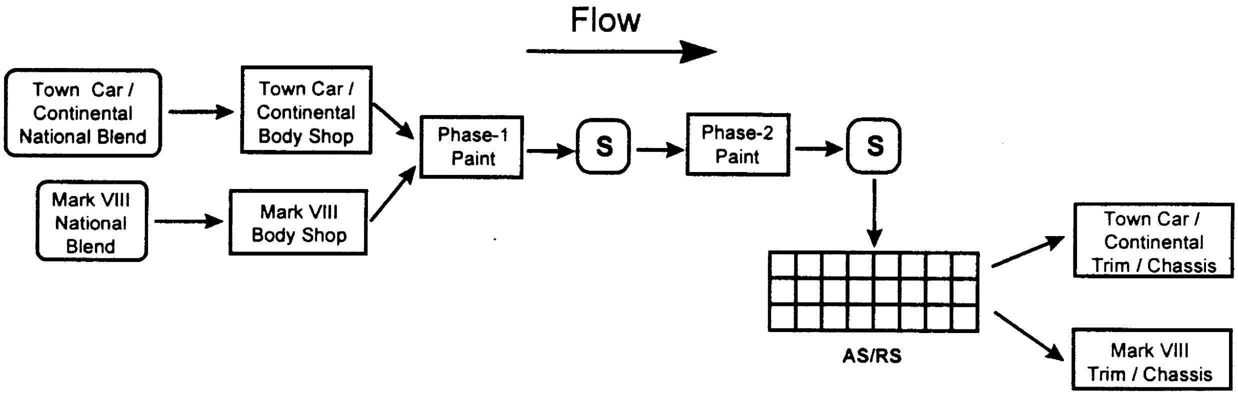


Figure 3-4: The flow of vehicles through Wixom

Since Wixom is an ILVS plant, it is important to review a few key points about ILVS. First, instead of becoming affixed with vehicle identification tags at the body shop, car bodies receive radio frequency (RF) transponders. Throughout their operations, the body and paint shops use the transponders to identify and route the vehicles. Second, the plant actively manages each of the off-line repair stations. That is, it now repairs vehicles as soon as possible to minimize sequence distortion from repair delays.

Recently, in response to softening demand, Wixom reduced the operation of the Mark VIII body shop down to only one shift. To maintain a constant flow of vehicles through the paint shop, which services all three vehicle types and must operate on two shifts, the plant diverts half of the Mark VIIIs to a storage area in the upper mezzanine, for release during the second shift. It feeds the remaining half directly to the paint shop.

As vehicle bodies leave the main body shop, they pass through a body-in-white bank on their way to the paint shop. This three-lane bank serves two functions. First, it buffers the paint shop against downtime in the body shop and generally serves to smooth the flow between the two shops. Second, it preserves the three-to-one rotation of Town Cars to Continentals by channeling the large cars down two of the lanes, the small cars down the other lane, and then releasing them in the proper pattern.

From the two body shops, vehicles merge into the paint shop in a yet another rotation. The system admits one Mark VIII after every eight Town Car/Continentals. In the Phase-1 paint shop, vehicle bodies receive phosphate and E-coat (Electrocoat) treatments for corrosion protection and are then sealed and scuffed in preparation for the next phase of paint. After Phase-1, the car bodies are ready for the first substitution station. Theoretically, the system should apply substitution to reduce the spread of vehicles out of sequence each time it adds distinguishing features to the vehicles (i.e., it increases their complexity level) and distorts their sequence. The body shops add the differentiating features of car type (Town Car, Continental, and Mark VIII) and moon-roof (or no moon-roof). Phase-1, on the other hand, does nothing to increase the body-in-white complexity of the vehicles since all cars need the same phosphate, E-coat, and sealant. Because the Phase-2 paint shop introduces a significant amount of complexity to the vehicles through the application of specific paint colors, the system makes a substitution just prior to this point in order to reduce the sequence distortion caused by the body shop and the Phase-1 paint shop.

After the first substitution station, car bodies enter the Phase-2 paint shop where they are primed and then painted in one of the two enamel booths. A portion of the cars are tri-coats and require a series of special upgrades to impart an opalescent quality to their paint finish. Only one of the paint booths can accommodate these vehicles. The Phase-2 paint shop introduces a significant source of sequence distortion. After the enamel ovens (which cure the paint finish), all vehicles pass through a seek-and-repair operation where a portion of the vehicles must be reworked. Some of these rejected cars require only minor rework, while others must be repainted. Those vehicles that do not require rework soon exit the paint shop, flow through the second and final substitution station, and move on to the Automated Storage and Retrieval System (AS/RS). The AS/RS sorts the painted vehicle bodies and delivers them to the trim and chassis area approximately 98% in sequence.

In the idealized case, the body and paint shops place no requirements on the sequence of vehicles that pass through them; they exist solely to build painted bodies for the final assembly area. The body and paint shops at Wixom, however, are not quite so accommodating. First, the main body shop insists on a three-to-one rotation between Town Cars and Continentals. As mentioned previously, this strict rotation is really needed only in final assembly. However, the body and paint shops have come to depend on this rotation to properly coordinate and utilize capacity. It is important to note how this rotation affects the concept of pre-sequencing. We no longer have the luxury of creating any sequence we like for the paint and body shops. Now, we are constrained by the requirement of having to rotate the vehicles according to the desired mix.

The Phase-1 paint shop has similar rigidities. Recall that both the main body shop and the Mark VIII body shop merge their output into Phase-1. In keeping with Wixom's convention of establishing rotations to maintain vehicle mix, the plant pulls in a single Mark VIII for every eight Town Car/Continentals. Also, as the vehicles approach the manual sealer line, the plant maintains (or establishes) another rotation to balance the work loads of the line employees. This time, the two-to-one mix between large cars and small cars is the issue. The workers require more time to seal the small cars than the large cars (due to the increased occurrence of hard-to-seal surfaces). Thus, they require the large cars to relieve them in a timely and consistent fashion. The plant achieves this goal by spacing out the merging of the Mark VIIIs and by using a special by-pass/surge lane right before the sealing line.

To understand how these requirements affect the pre-sequencing concept, imagine a long block of ten cars, all to be painted white, arriving from the main body shop. Four cars make their way into the Phase-1 paint shop when a lone Mark VIII, to be painted green, suddenly arrives. This breaks up the long block of white cars. The cars move on to receive their phosphate, E-coat, and under-body sealant and approach the manual seal line. However, because of upstream disruption, they fail to arrive in the appropriate two-to-one large car/small car rotation and must be rearranged. This shuffling compromises the in-sequence percentage and continues to degrade the paint blocks.

The Wixom ILVS implementation deviates from the ideal in yet another way. In several paint shop locations, vehicle flow diverges into two or more parallel lanes. Ovens, prime booths, and strip lanes are examples of processes that utilize parallel structures for additional capacity. Ideally, the operations in a parallel process have deterministic and identical cycle times, but in reality they vary according to a statistical distribution and are subject to down-time. ILVS guidelines recommend that the plant deal with such uncertainties by admitting cars into such parallel processes in an alternating fashion and removing them in the same manner. In practice, however, Wixom follows a "first-available" policy to avoid compromising the system throughput. Therefore, if the next lane in the alternating pattern happens to be blocked, the vehicle will move to the first available lane. This results in a shuffling effect similar to the one described in the previous paragraph.

The final deviations from our idealized model occur in the Phase-2 paint shop. First, Wixom (and most other Ford plants) uses two paint booths. This design can create sequencing disruptions in the following sense. Suppose we manage to create a modified blend that contains only ten-car paint blocks. If these blocks were to reach the paint booths intact, they would then be broken in half as they alternate through the two booths. Second, the processing of tri-coats calls for a number of special processing steps, causing the affected cars to become out of sequence.

The following chapter calculates the cost of purging the paint automation equipment at Wixom and establishes a better metric than average block size for evaluating Block Painting performance. Chapter 5 then simulates the pre-sequencing Block Painting methodology for an ideal case. The simulation demonstrates that pre-sequencing can work in an ideal ILVS environment and suggests possibilities for implementation at Wixom.

Chapter 4

CALCULATION OF PURGE COSTS

Evaluating the merit of a Block Painting implementation on average block size does not align well with the idea of reducing bulk material costs. The average block size metric reports the quantity of bulk material consumed by the purging process during a production cycle, and implicitly assumes that each paint purge costs the same. On the contrary, paint purges vary dramatically in cost, depending on the chemical composition of the paint being purged. For instance, certain types of green paint cost much more than ordinary white paint due to their high organic content and limited availability. Consequently, purging the automation equipment of these green paints costs more than doing so for the white paints even though the same physical quantity of paint material is discarded. In this chapter, we calculate the purge costs for each of the paint colors at Wixom. We then present an alternative metric, based on relative purging costs, for evaluating Block Painting.

4.1 Calculating Paint Purge Bulk Material Costs

Paint application equipment is complex and varied in nature. The level of automation ranges from manual paint guns, for use by human operators, to fully automated robots. Moreover, a variety of techniques are available for atomizing, or spraying, the paint. Each combination of automation and application technology serves a different need in the paint shop.

In general, purging the automation equipment involves removing the old paint color, loading the new paint color, and testing the spray pattern. Each step wastes solvent and paint. Wixom's base-coat application process uses a combination of automation types. Figure 4-1 shows the normalized purge costs for the paint colors at Wixom. The calculation takes into account the quantities of paint and solvent used by each of the automation types as well the costs of these materials [23]. The reader should note that the cost of purging varies considerably from one color to the next.

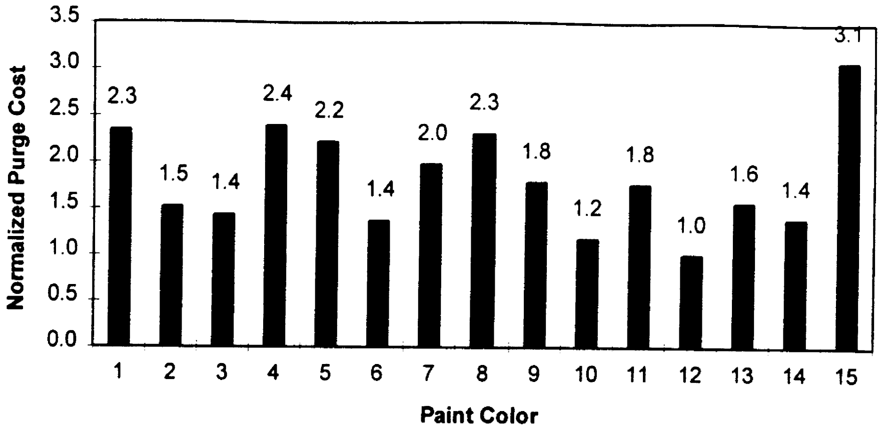


Figure 4-1: Normalized paint purge costs at Wixom

4.2 A Better Block Painting Evaluation Metric

To minimize total purging costs, the system should give higher priority to reducing the number of expensive purges than to reducing the number of inexpensive purges. Consider the following stream of twelve vehicles, each to be painted with one of two enamel colors:

A B A B A B A B A B A B

Paint color A costs $10 to purge, while paint color B costs $20 to purge. Since there are no paint blocks of size greater than one in this sequence, the average block size is just 1.0. Correspondingly, the total purging cost is $180.

Now suppose a simple Block Painting scheme were able to produce this next sequence:

A A A B B B A A A B B B

The average block increases to 3.0, while the total purging cost reduces to $60.

Finally, consider the following two sequences:

A A A B B B B B B A A A

B B B A A A A A A B B B

Even though both streams have an average block size of 4.0, the first costs $40 to purge, while the second costs $50.

The disparity between the two purging costs confirms the need for a new metric. Average block size is just the ratio of the total number of cars painted to the total number of purges. An analogous measure, but one that takes into account purge costs, divides the maximum possible purging cost (i.e., the accumulated cost of purging after every vehicle) by the actual purging cost. Notice what happens in each of our examples when we apply this new measure. The first blocked sequence yields a value of 3.0 ($180/$60). The fact that this ratio exactly equals the average block size value signifies that the reshuffling has made no attempt to create larger blocks of either color. Repeating this calculation for the last two sequences yields ratios of 4.5 ($180/$40) and 3.6 ($180/$50). Given two possible ways of creating an average block size of 4.0, the first sequence builds a larger block of the more expensive color, while the second sequence builds a larger block of the cheaper color. The revised metric correctly identifies the purge savings.

Therefore, when implementing Block Painting, the plant should use this metric to properly direct cost reduction efforts. For the sake of consistency, however, we use the traditional metric – average block size – throughout the remainder of this thesis.

Chapter 5

SIMULATION OF ILVS BLOCK PAINTING METHODOLOGIES

Chapter 2 introduced the conflicting concepts of In-Line Vehicle Sequencing and Block Painting. Chapter 3 then considered the possibility of combining the two initiatives without sacrificing the key goals of maintaining sequence control and minimizing paint purges. It described the popular idea of using substitution to create paint blocks, highlighted some significant disadvantages of this method, and then presented an entirely new approach to the problem. This chapter aims to establish, through simulation, that pre-sequencing outperforms the substitution methodology for Block Painting. The first section presents the framework of the model, including its objectives, and describes the constituent modules. The next section examines the data requirements for the model. The subsequent section describes each of the experiments run on the model. The final section compares and interprets the results from the simulation experiments.

5.1 Simulation Framework

Simulation is the process of building a model that replicates the behavior of an existing or a proposed system and experimenting with the model to understand and improve the system. The purpose of this project is to evaluate the effects of incorporating Block Painting into an ILVS environment. What becomes of sequence control? Can vehicles be painted in significant blocks of like color? To answer these questions, we need to construct a model of an ILVS system so that we can evaluate modifications to the system.

We chose to use discrete-event modeling for this purpose. Because of the highly non-linear and unpredictable nature of the flow of vehicles through the ILVS system, discrete-event simulation allows us to understand how the various disruptions in the plant impact vehicle sequence and how In-Line Vehicle Sequencing counters these sequence disruptions. It also enables us test how well different Block Painting methodologies would deliver cars to the paint booth, in blocks of like color, and to what degree they could do so without compromising sequence control capabilities.

5.1.1 Objectives of the Simulation Model

The simulation model helps evaluate how ILVS controls sequence and how Block Painting creates and maintains paint blocks. When implemented together, ILVS and Block Painting could strongly interact with each other. Certainly, many believe that either Block Painting would adversely affect the sequencing objectives of ILVS, or ILVS would hamper the ability of Block Painting to do its job. This is but one set of possibilities. Some configuration of ILVS might actually promote Block Painting. In such a context, Block Painting could either minimally detract from, be completely benign towards, or even aid ILVS objectives. The simulation model permits us to "test-drive" different Block Painting methodologies in order to understand the nature and magnitude of the their interactions with ILVS.

The simulation model therefore aims to show how vehicle sequence becomes disrupted, and how paint blocks can be propagated, along each stage of the assembly process. We use two primary metrics to measure system performance. For sequence control, the minimum AS/RS size needed to restore vehicle build sequence, after the paint shop, to 98% in-sequence gives a very good idea of the magnitude of body and paint shop distortion. For Block Painting, the average paint block size arriving at the paint booth demonstrates the effectiveness of the Block Painting technique.

5.1.2 Structure of the Simulation Model

The simulation model is based on the ILVS implementation at Ford's Wixom assembly plant. Recall from the description of the vehicle flow in Chapter 3, that Wixom builds according to two National Blends – one for the Town Cars and Continentals and the other for the Mark VIIIs. The plant has a separate body shop for each National Blend, the outputs of which merge at the entrance to an integrated paint shop. After both phases of paint, the vehicles become re-sequenced in the AS/RS, enter the final assembly area and are diverted into two separate trim and chassis areas – once again according to National Blend affiliation.

The simulation model reflects this flow. It contains four main modules – one for each body shop, and one for each phase of paint. A consulting firm – Cleaver, Ketko, Gorlitz, Papa & Associates (CKGP) – developed these modules using a discrete-event simulation application called Witness (by AT&T Istel). In addition to these modules, we created a number of helper applications to simulate the two substitution stations (one after the Phase-1 paint shop, the other after the Phase-2 paint shop) and the AS/RS re-sequencing facility. We also implemented several analysis tools evaluate the key performance metrics at each stage of the simulation. Appendix A describes each of the basic simulation modules, helper applications, and analysis tools used to run the simulation. Appendix B specifies the common data format used by all of the components.

5.1.3 Model Construction and Validation

CKGP played an instrumental role in establishing ILVS at Wixom. The purpose of their project was "to develop the best strategy for implementing In-Line Vehicle Sequence (ILVS) Control at the Wixom assembly plant and to define and quantify the costs and benefits of implementing ILVS at Wixom" [26]. Their major effort led to a variety of useful insights, conclusions, and tools. Among them were the four basic simulation modules used in our analysis.

The CKGP project included a thorough analysis of the production system as it existed before ILVS. CKGP dispatched teams to collect information on sequence distortion points, repair delays, and first run capabilities. From this and other information, it constructed a simulation of the pre-ILVS process and suggested ILVS measures to improve the process. Revisions to the model reflected these suggestions. The model is generally viewed by Ford as being representative of the ILVS system at Wixom. The process used for verification and validation is best explained in CKGP's own words:

> "The models that were developed for the Wixom study were not intended to mimic the systems under study, but to represent the disruption caused by the systems under study. Also, many of the models were written of areas that do not exist, therefore validation would be impossible. Verification of the plant models was carried out by showing the models to various plant personnel familiar with the workings of the areas under study and also by explaining the logic used for modeling the different areas. All the problems of the day-to-day running of the assembly operation have not been captured in the models, but the factors that are detrimental to sequence maintenance have been covered and are accurate" [26].

Although the simulation modules effectively capture the major barriers to sequence, some of the assumptions and simplifications that they use lean more toward an ideal ILVS implementation than to actual Wixom practice. For instance, CKGP worked into the model their suggestion that "parallel ovens, cooling tunnels and surge areas need to be controlled to maintain sequence" [26]. In other words, whenever vehicles diverge into parallel processes or lanes, the system should maintain sequence by alternating vehicles in and out of these lanes. In contrast, Wixom generally sends a car into or pulls one out of the first available lane. Because of variation in the cycle times and downtime in the parallel processes, the first of several cars to enter a parallel system might not be the first one to reach the exit. The model assumes equal cycle times and no downtime for these processes. The net effect of these simplifications is minor in terms of sequence control capabilities (i.e., the first available policy does not lead to significant sequence distortion), but the shuffling that occurs is detrimental to paint blocks.

The Witness-based modules provided by CKGP effectively simulate the disruptions in the assembly process. The combination of these modules, helper applications, and analysis tools allows us to explore the interactions between ILVS and Block Painting.

5.2 Simulation Data

The simulation study requires information about the desired vehicle build sequence and the process by which the sequence can become distorted. The latter is used to construct the simulation model, and the former is used as input to the model. The vehicle sequence data was relatively straightforward to acquire. As noted in Chapter 2, the purpose of ILVS is to send vehicles to the trim/chassis area of the plant in a strictly maintained order. When a vehicle arrives at trim, the AVS/AVI system records its National Blend rotation number, along with a newly assigned trim rotation number, in a central database file. We collected approximately six weeks worth of trim sequence information from the database and were able to reconstruct the original National Blend sequence for that time span.

Appendix B describes the sequence data in detail. Recall from Chapter 2 that the number and frequency of paint colors, distinct body-in-white configurations (body-in-white complexity), and distinct painted body configurations (painted body complexity) influence the effectiveness of the substitution mechanism. The appendix lists the various enamel colors and body-in-white and painted-body complexity levels for the data stream. We chose to divide the data stream into three separate National Blend sequences. Since the National Blend for any given week of production is derived from customer orders, the relative frequencies of each body-in-white, enamel, and painted-body complexity level vary over time. For example, green cars might comprise 20% of the blend during one period and only 10% the next. Since two weeks worth of blend information (approximately 7300 vehicles) is likely to be sufficient for the simulation model to give meaningful results, we segmented the data stream to enable the correlation of certain outcomes with changes in customer ordering patterns. A time span of six weeks would tend to smooth out shifts in blend composition.

5.3 Simulation Experiments

The simulation experiments we describe in this section assume an intimate understanding of the flow of vehicles through Wixom. Section 3.2.5 discussed this flow in detail, while Figure 3-4 provided a summary.

So far we have discussed the basic framework of the simulation model. Now we delve into the heart of the project – the experimentation with the simulation model. The first experiment simulates the base case, and since it represents the way Wixom is running today, simply strives to establish a common ground for ILVS system performance. The next two simulation experiments deal with Block Painting. The first Block Painting experiment, which evaluates the conventional substitution methodology for Block Painting, is the same as the base case experiment in all respects except for the operation of the first substitution station. Recall from Chapter 2 that we modify this substitution station – the one before the paint booth – not only to restore sequence, but also to create paint blocks. The second Block Painting experiment utilizes pre-sequencing to propagate blocks all the way from the body shop to the paint booth. This experiment simulates an ideal ILVS environment, showcasing the capabilities of the pre-sequencing methodology in an environment especially designed for it. The last experiment is the same as the base case, except for the removal of the first substitution station. The pre-sequencing methodology must deactivate the first substitution station in order to protect its paint blocks (see

Section 5.3.3). Therefore, this last experiment provides a special base case for isolating the effects of pre-sequencing on sequence control.

During the preliminary simulation runs, we noticed a curious phenomenon. The Phase-2 paint shop simulation module took longer to run for blends with significant color blocks than for blends without color blocks. Apparently, the processing times of certain processes depend on the paint colors of the vehicles that pass through them. Further investigation revealed that the tri-coat upgrade operations were responsible for the problem. By barraging the affected processes with blocks of "slow" colors, we inadvertently bogged down the system. Clearly, before Block Painting can be properly implemented in an ILVS context, the plant would have to remove such dependencies. However, for the purpose of simulating the effects of Block Painting on sequence control, we had to eliminate these relationships in the simulation model. The simulation strives to understand how adding distortion to the system, by creating paint blocks, affects overall sequence control. That is, the relationship between the addition of sequence distortion (via paint blocking) and the system's ability to handle that distortion is of key interest. An additional dependence between paint color and system performance confounds the primary relationship.

To circumvent this problem, we developed the following approach to running experiments on the simulation model:

1. *Use a generic input sequence – that is, one without any embedded color blocks – to generate a series of unbiased distortion templates for each simulation module.* A distortion template is just a representation of the distortion that occurs on a input sequence. It describes how far each car in the input sequence moves from its original position due to sequence disruption in the module. The simulation software uses a random number generator in conjunction with a variety of transformation functions to generate samples from statistical distributions. These distributions in turn govern the behavior of the machines and processes in each simulation module [12]. With a common input sequence and a unique random-number stream for each replication, we compare each replication's output sequence with the common input sequence to create the distortion templates.

2. *Apply each of the distortion templates to a blocked input sequence.* This effectively simulates a given Block Painting methodology in an environment free of color-based processing time dependencies (i.e., a system unaffected by blocks of tri-coats).

We thus created five distortion templates for each simulation module using the National Blend as the common input sequence. We then applied each of these distortion templates to the appropriate paint-blocked input sequences to simulate the various Block Painting approaches.

The simulation model records average paint block size as if the system were using a single booth, even though Wixom uses a dual-booth painting system. By temporarily avoiding the issue of how to prevent the paint blocks from becoming split at the booths, we can first concentrate on how to deliver the blocks to the booth. Later, we can adjust the system to accommodate multiple booths.

In order to evaluate the relative sequence control capabilities of the base case and each of the Block Painting configurations, we vary the size of an ideal AS/RS to achieve 98% in-sequence. An ideal AS/RS is filled to capacity and the vehicle input rate is precisely the same as the vehicle output rate. The size AS/RS needed to achieve this idealized capacity utilization serves as a useful metric for the quality of sequence control even though it understates actual AS/RS requirements. In practice, the system would require additional AS/RS space to smooth production and buffer against downtime. The purpose of this project is to highlight relative differences in sequence control and Block Painting capabilities, not to predict actual AS/RS requirements or achievable block sizes.

5.3.1 Base Case

The base case represents the current ILVS system at Wixom. Accordingly, the base case simulation experiment assumes the full vehicle mix constraints in the body and paint shops (that is, the three-to-one rotation of Town Cars to Continentals and the eight-to-one rotation of Town Car/Continentals to Mark VIIIs). Moreover, the simulation makes no attempt to create paint blocks. This experiment does not seek to re-validate the simulation model by expecting results that mirror actual Wixom production output (see Section 5.1). Rather, the base case provides a common reference point against which we can evaluate the relative Block Painting and sequence control performance characteristics of competing Block Painting strategies.

The input to the base case model is just the National Blend sequence. The main body shop receives the Town Car/Continental National Blend and the Mark VIII body shop receives its own National Blend sequence. Recall that the main body shop requires a three-to-one rotation between the Town Cars and the Continentals. The incoming National Blend, which already contains this rotation, automatically satisfies this constraint.

After the body shops, one Mark VIII body-in-white merges with every eight Town Car/Continental bodies-in-white. If a precise three-to-one mix were maintained in the main body shop, then this merging process would ensure a predictable two-to-one mix between large cars and small cars (see Section 3.2.5). Recall that the Phase-1 paint shop imposes this requirement in order to balance labor usage at the manual sealer deck. The simulation satisfies this constraint by forcing the output of the main body shop into a three-to-one rotation. After Phase-1, the vehicles pass through the first substitution station, make their way through the Phase-2 paint shop, pass through the second substitution station, and then head into the AS/RS.

Table 5-1 presents the results of the base case simulation runs. We ran five replications for each of the three data sets. The table shows the AS/RS size required to restore the vehicles to 98% in-sequence, the average paint block size at the entrance of Phase-2, the average block size reaching the paint booth, and the projected annual purge costs (assuming a volume of 200,000 vehicles). To compare the Block Painting methodologies we evaluate the average paint block size at two locations: before paint and at the paint booth. Each Block Painting method has a unique approach to establishing paint blocks at the entrance to Phase-2. The substitution method creates paint blocks near the Phase-2 entrance, while the pre-sequencing method delivers paint blocks to this point. From there, both methodologies use the same technique to transport the paint blocks to the enamel booth. The average block size at the entrance to Phase-2 indicates the effectiveness of the paint blocking effort, while the block size at the paint booth characterizes the block maintenance capability of Phase-2. In the base case, the block sizes at both locations are roughly the same. This implies that the paint blocks occur by chance, without the help of an active paint blocking mechanism.

Data Set	Trial #	AS/RS Size	Block Size Before Paint	Block Size at Paint Booth	Annualized Purge Costs
1	1	157	1.16	1.17	$ 2,647,600
	2	156	1.17	1.17	$ 2,643,800
	3	171	1.17	1.18	$ 2,623,700
	4	168	1.15	1.16	$ 2,665,100
	5	175	1.19	1.19	$ 2,611,600
2	1	162	1.23	1.23	$ 2,527,700
	2	147	1.23	1.22	$ 2,537,000
	3	173	1.26	1.25	$ 2,491,200
	4	158	1.23	1.22	$ 2,537,400
	5	173	1.26	1.25	$ 2,495,200
3	1	160	1.26	1.25	$ 2,488,400
	2	157	1.27	1.26	$ 2,476,000
	3	170	1.30	1.28	$ 2,431,800
	4	164	1.27	1.25	$ 2,482,200
	5	174	1.30	1.29	$ 2,421,400

Table 5-1: The base case simulation results

Table 5-2 provides a summary of the base case simulation results:

AS/RS Size	164
Paint block size at the paint shop entrance	1.23
Paint block size at the paint booth	1.23
Annualized purging cost	$ 2,538,700

Table 5-2: A summary of the base case results (average values)

5.3.2 Block Painting by Substitution

The conventional Block Painting methodology aims to build paint blocks at the first substitution station. It uses a modified substitution algorithm not only to improve sequence control, but also to bring like colors together. The simulation structure is exactly the same as that of the base case except for the helper application used to simulate the paint blocking effect at the first substitution station.

The algorithm attempts to build paint blocks of size ten using several search window sizes. Figure 5-1 shows the resulting paint block profile for a replication that uses a search window of size 75. The vertical axis shows the fraction of vehicles in the blocked sequence that constitute paint blocks of the size specified by the horizontal axis. For instance, approximately 23% of the vehicles lie in paint blocks of size one, while only about 1% form blocks of size ten. In other words, the substitution methodology is unable to build many blocks of the target block size. In this example, the substitution algorithm produces an average block size of 2.08.

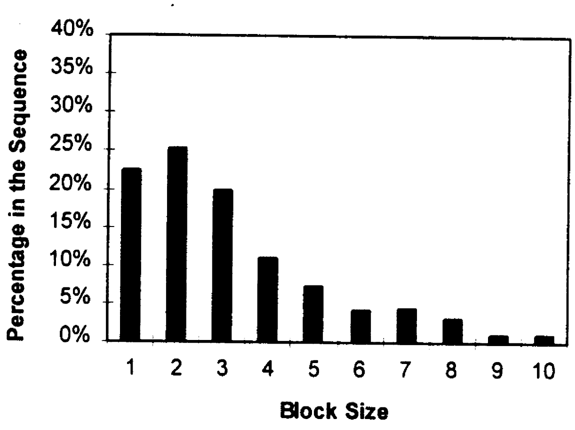


Figure 5-1: A paint block profile of the substitution method; target block size=10; search window=75; average block size=2.08

Figure 5-2 shows the paint block profile for these same vehicles as they reach the paint booth. Since the number of vehicles in single blocks increases considerably, the average block size drops to 1.86.

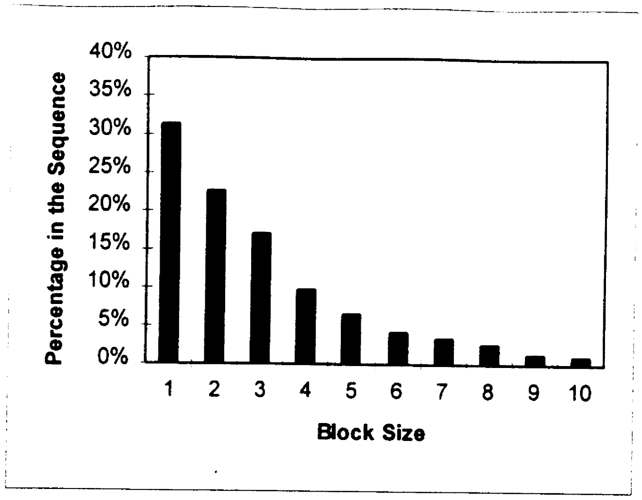


Figure 5-2: A paint block profile of the substitution method at the enamel booth; average block size=1.86

We ran the experiment using five different search windows sizes. For each replication, we record the average block size produced by the modified substitution algorithm near the Phase-2 entrance as well as the average block size reaching the paint booth. In addition, we note the AS/RS sizes needed to restore to 98% in-sequence. Tables 5-3, 5-4, 5-5, 5-6, 5-7 show the results for each of the search windows. Recall that the search window size determines how far the substitution mechanism can look for like colors when creating paint blocks.

Data Set	Trial #	AS/RS Size	Block Size Before Paint	Block Size at Paint Booth	Annualized Purge Costs
1	1	157	2.08	1.86	$ 1,699,600
	2	151	2.09	1.87	$ 1,689,200
	3	180	2.08	1.85	$ 1,697,800
	4	166	2.12	1.88	$ 1,678,500
	5	168	2.09	1.86	$ 1,691,400
2	1	162	2.25	1.94	$ 1,636,800
	2	160	2.28	1.97	$ 1,615,800
	3	161	2.28	1.98	$ 1,606,600
	4	157	2.30	1.99	$ 1,598,400
	5	175	2.29	1.98	$ 1,618,200
3	1	160	2.26	1.98	$ 1,604,800
	2	158	2.26	1.97	$ 1,598,900
	3	167	2.27	1.97	$ 1,595,600
	4	171	2.23	1.96	$ 1,604,300
	5	173	2.27	1.97	$ 1,610,700

Table 5-3: The substitution method simulation results; search window=75

Data Set	Trial #	AS/RS Size	Block Size Before Paint	Block Size at Paint Booth	Annualized Purge Costs
1	1	154	2.42	2.06	$ 1,538,300
	2	165	2.39	2.06	$ 1,540,900
	3	189	2.38	2.05	$ 1,540,200
	4	184	2.37	2.05	$ 1,544,000
	5	169	2.36	2.04	$ 1,547,000
2	1	172	2.68	2.21	$ 1,449,800
	2	159	2.65	2.21	$ 1,443,500
	3	182	2.69	2.22	$ 1,442,300
	4	168	2.66	2.21	$ 1,446,400
	5	177	2.63	2.19	$ 1,461,400
3	1	167	2.63	2.19	$ 1,446,500
	2	177	2.57	2.16	$ 1,469,600
	3	185	2.62	2.18	$ 1,451,600
	4	170	2.63	2.20	$ 1,432,500
	5	178	2.63	2.19	$ 1,448,900

Table 5-4: The substitution method simulation results; search window=150

Data Set	Trial #	AS/RS Size	Block Size Before Paint	Block Size at Paint Booth	Annualized Purge Costs
1	1	224	2.67	2.22	$ 1,422,400
	2	215	2.69	2.24	$ 1,415,600
	3	224	2.68	2.25	$ 1,411,800
	4	225	2.71	2.23	$ 1,417,100
	5	232	2.69	2.24	$ 1,410,400
2	1	235	3.05	2.42	$ 1,324,200
	2	227	3.15	2.47	$ 1,301,200
	3	242	3.03	2.42	$ 1,323,700
	4	224	3.03	2.41	$ 1,332,300
	5	237	3.06	2.43	$ 1,321,300
3	1	228	3.01	2.39	$ 1,322,600
	2	219	2.94	2.36	$ 1,353,100
	3	216	2.96	2.37	$ 1,340,700
	4	230	2.95	2.38	$ 1,330,700
	5	236	2.97	2.40	$ 1,333,600

Table 5-5: The substitution method simulation results; search window=300

Data Set	Trial #	AS/RS Size	Block Size Before Paint	Block Size at Paint Booth	Annualized Purge Costs
1	1	388	2.94	2.39	$ 1,339,200
	2	422	2.96	2.39	$ 1,322,200
	3	382	2.95	2.38	$ 1,336,500
	4	391	2.96	2.38	$ 1,338,800
	5	410	2.97	2.38	$ 1,331,300
2	1	436	3.37	2.59	$ 1,239,200
	2	416	3.41	2.60	$ 1,235,900
	3	415	3.39	2.60	$ 1,240,100
	4	442	3.40	2.61	$ 1,227,300
	5	452	3.42	2.61	$ 1,225,400
3	1	428	3.25	2.54	$ 1,258,500
	2	420	3.23	2.53	$ 1,258,500
	3	406	3.24	2.52	$ 1,263,500
	4	421	3.29	2.54	$ 1,250,000
	5	397	3.26	2.54	$ 1,251,800

Table 5-6: The substitution method simulation results; search window=600

Data Set	Trial #	AS/RS Size	Block Size Before Paint	Block Size at Paint Booth	Annualized Purge Costs
1	1	754	3.14	2.50	$ 1,275,500
	2	722	3.14	2.49	$ 1,274,500
	3	751	3.12	2.48	$ 1,274,500
	4	751	3.13	2.48	$ 1,287,000
	5	764	3.15	2.50	$ 1,268,300
2	1	751	3.56	2.68	$ 1,206,700
	2	749	3.60	2.70	$ 1,203,200
	3	730	3.63	2.71	$ 1,189,800
	4	733	3.56	2.70	$ 1,185,600
	5	769	3.61	2.72	$ 1,182,000
3	1	844	3.62	2.71	$ 1,180,400
	2	792	3.56	2.68	$ 1,184,300
	3	766	3.55	2.70	$ 1,176,200
	4	816	3.53	2.67	$ 1,191,400
	5	848	3.51	2.69	$ 1,184,100

Table 5-7: The substitution method simulation results; search window=1200

Table 5-8 summarizes the results of the substitution Block Painting methodology.

	Search 75	Search 150	Search 300	Search 600	Search 1200
AS/RS Size	164	173	228	415	769
Paint block size at the paint shop entrance	2.21	2.55	2.91	3.20	3.43
Paint block size at the paint booth	1.94	2.15	2.35	2.51	2.63
Annualized purging cost	$1,636,400	$1,480,200	$1,357,400	$1,274,600	$1,217,600

Table 5-8: A summary of the substitution method results (average values)

Figure 5-3 shows the relationship between search window size and block size. For small search windows (less than 100), the block size improvement over the base case is substantial. As the search window enlarges beyond that, however, the gains in block size rapidly diminish.

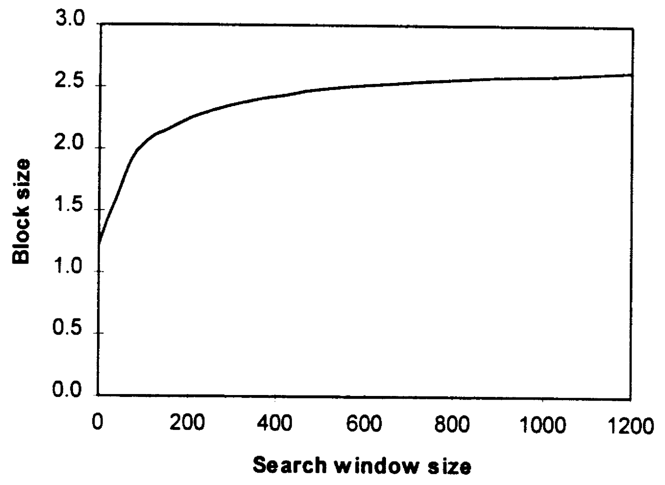


Figure 5-3: Block size vs. Search window size

Figure 5-4 shows the relationship between search window size and AS/RS size. For small search window (less than 125), the AS/RS requirements remain unchanged from the base case. For larger search windows, however, the AS/RS requirements grow in direct proportion to the increase in search window size.

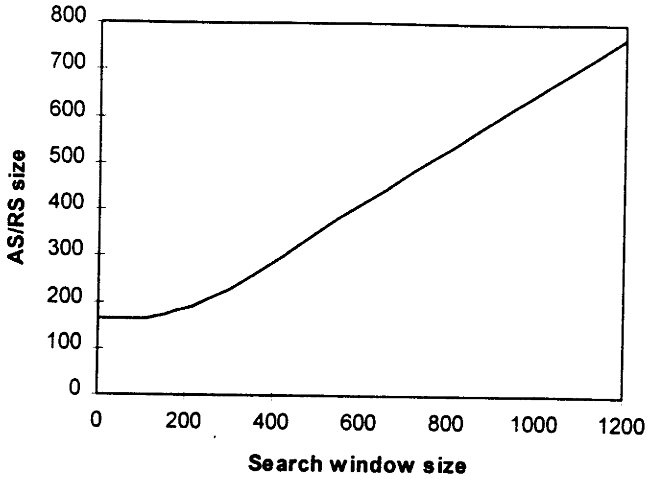


Figure 5-4: AS/RS size vs. Search window size

5.3.3 Block Painting by Pre-sequencing

The pre-sequencing simulation experiment evaluates the new approach to Block Painting proposed in Chapter 3. The basic idea underlying the concept is to create paint blocks from the National Blend sequence before the sequence enters the system. After the blocked sequence enters the body shop, ILVS sequence control capabilities maintain the integrity of the paint blocks throughout the build process. When they reach the paint booth, the paint blocks are large enough to satisfy Block Painting objectives. For the Town Car/Continental National Blend, we set the target block size to value 10 and we set the search window to value 70. For the Mark VIII, we adjust the search window to result in the same average paint block size as the Town Car/Continental stream in order to replicate the characteristics of an ideal ILVS environment (which caters to only one national blend).

Figure 5-5 shows the paint block profile of the sequence reaching the entrance to Phase-2 for one of the simulation replications. Unlike the corresponding profile for the substitution methodology (represented in Figure 5-1), the majority of the vehicles form paint blocks of the target size. Even though both examples use approximately the same search window size (70 for pre-sequencing, 75 for substitution), the pre-sequencing approach builds large blocks with much greater ease. The average block size is 6.0.

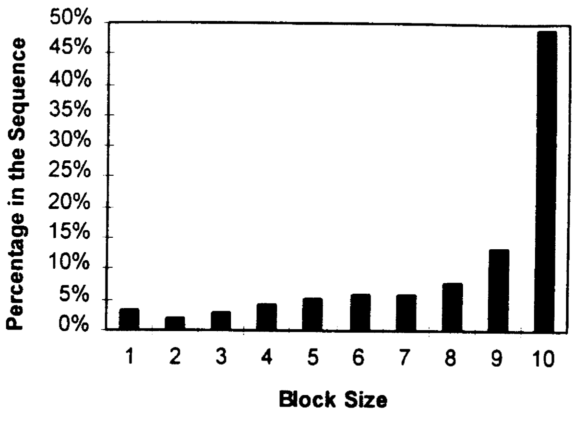


Figure 5-5: A paint block profile of the pre-sequencing method at the entrance to Phase-2; target block size=10; search window=70; average block size=6.0

Figure 5-6 illustrates the paint block profile for the same vehicles as they approach the enamel booth. As expected, the number of vehicles in single blocks increases, while the numbers in each of the remaining block sizes decrease. Thanks to block protection, however, the shape of the paint block profile barely changes. The average block size reduces to 3.54.

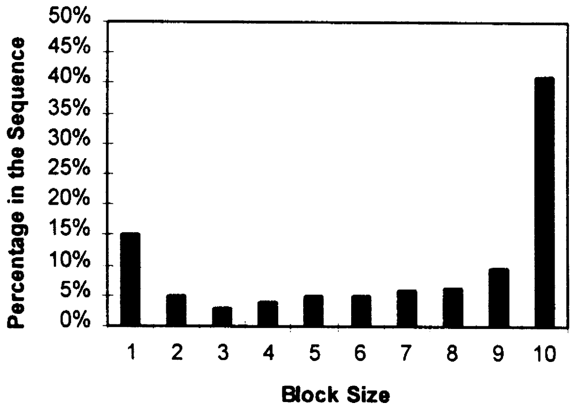


Figure 5-6: A paint block profile of the pre-sequencing method at the paint booth; average block size=3.54

Figure 5-7 depicts this same scenario, but without block protection. The differences in the two paint block profiles are dramatic; the single paint blocks grow in number, while the larger paint blocks whittle away. The resultant average block size is 2.72.

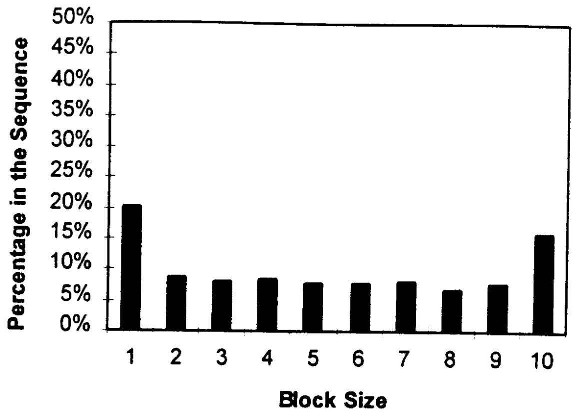


Figure 5-7: A paint block profile of the pre-sequencing method at the paint booth; no block protection; average block size=2.72

The pre-sequencing Block Painting methodology assumes ideal ILVS conditions. Consequently, the body and paint shops impose no vehicle mix constraints on the system. Also, the plant builds to only one National Blend and actively manages all parallel lanes for sequence control. In order to force the Wixom simulation modules to simulate ideal ILVS condition, we cannot just remove the Mark VIIIs from the model; the cycle times in the model depend on the existence of the Mark VIIIs, so removing them would lead to unreliable results. Rather, we pre-sequence the Mark VIIIs to produce the same average block size as the Town Car/Continentals. For example, suppose we are able to produce an average block size of 7.5 for the Town Cars/Continentals. We then adjust the pre-sequencing parameters for the Mark VIIIs to achieve the same average block size.

Recall that in the normal Wixom production flow, one Mark VIII body-in-white follows every eight Town Car/Continentals into the Phase-1 paint shop. When using pre-sequencing to create paint blocks, we must merge in an entire Mark VIII paint block rather than just one Mark VIII at time. For example, suppose a block of three white Mark VIII vehicles approaches the end of the Mark VIII body shop. If we were to follow normal Wixom practice, we would pull in one of these white cars into the paint shop, then admit eight Town Car/Continentals, then the second white Mark VIII, and so on. This merge-in policy would effectively disintegrate the Mark VIII paint block. Rather, we must accumulate the entire Mark VIII paint block in a buffer and, at the appropriate moment, release it into the paint shop.

In order for the pre-sequencing system to preserve the integrity of the paint blocks, it must deactivate the first substitution station. Since cars that arrive at this substitution station have not yet passed through the enamel booth, the substitution mechanism is free to assign these cars the paint colors of cars with the same BIW type but of lower sequence number. One can easily imagine the effect of this capability on paint blocks. The next simulation measures to what degree omitting the first substitution station affects sequence control. Table 5-9 shows the results of the pre-sequencing experiment for all of the replications.

Data Set	Trial #	AS/RS Size	Block Size Before Paint	Block Size at Paint Booth	Annualized Purge Costs
1	1	168	6.00	3.54	$ 881,800
	2	164	6.10	3.63	$ 856,400
	3	193	6.00	3.59	$ 875,800
	4	183	6.11	3.62	$ 863,200
	5	183	6.01	3.61	$ 868,600
2	1	176	5.89	3.54	$ 883,400
	2	166	6.03	3.60	$ 865,100
	3	175	5.90	3.55	$ 881,500
	4	178	6.10	3.62	$ 860,500
	5	178	5.96	3.57	$ 867,200
3	1	177	6.01	3.57	$ 877,000
	2	169	6.16	3.65	$ 855,900
	3	174	6.07	3.61	$ 864,300
	4	179	6.12	3.67	$ 857,300
	5	170	6.09	3.59	$ 867,000

Table 5-9: The pre-sequencing simulation results

Table 5-10 summarizes the results of the pre-sequencing Block Painting methodology:

AS/RS Size	176
Paint block size at the paint shop entrance	6.04
Paint block size at the paint booth	3.6
Annualized purging cost	$ 868,300

Table 5-10: A summary of the pre-sequencing results (average values)

5.3.4 Modified Base Case – First Substitution Station Removed

This experiment omits the first substitution station from the original base case simulation described in Section 5.3.1. The purpose of this modified base case simulation is twofold. First, it quantifies the effectiveness of the first substitution station. Second, it helps isolate the effect on sequence control of using pre-sequencing to achieve Block Painting. Recall that the pre-sequencing methodology must deactivate the first substitution station in order to preserve its paint blocks. By having a base case that also deactivates this substitution station, we can directly evaluate the additional distortion imparted by the pre-sequencing process. Table 5-11 presents the results of this experiment.

Data Set	Trial #	AS/RS Size
1	1	159
	2	166
	3	183
	4	172
	5	178
2	1	168
	2	154
	3	167
	4	165
	5	173
3	1	161
	2	157
	3	175
	4	165
	5	177

Table 5-11: The results of the modified base case experiment

The modified base case requires an average AS/RS size of value 168.

5.4 Output Characteristics

Several aspects of the simulation results are worth noting. First, the substitution methodology with the 75-car search window has the same AS/RS requirements as the base case. The blocking effect enabled by this small search window increases the average paint block size from 1.23 to 1.94 and yet does not create any additional sequence distortion. The savings from implementing this methodology are significant – about $900,000. The 150-car search window creates an additional savings of approximately $150,000 and marginally increases the AS/RS requirements. Beyond this search window size, the AS/RS requirements grow proportionally with the increase in search window size, while the block sizes quickly plateau. The substitution methodology thus produces significant savings at little or no cost, but cannot meet the stated Block Painting objectives (i.e., achieving an average block size greater than three).

The pre-sequencing methodology results in savings of approximately $1,650,000 over the base case and seems to increase the minimum AS/RS size only slightly. In fact, the pre-sequencing approach and the substitution methodology with the 150-car search window have about the same impact on sequence control. Considering the amount of distortion added to the system by pre-sequencing, the increased AS/RS requirements seem very modest.

Finally, the results of the modified base case experiment show that the first substitution station does little to enhance sequence control. Therefore, we can safely deactivate it when implementing the pre-sequencing Block Painting methodology.

Chapter 6

USING PRE-SEQUENCING TO IMPROVE SEQUENCE CONTROL

The simulation experiments had two major objectives: to evaluate whether or not the substitution method might achieve Block Painting in an ILVS context and to test a new approach to the Block Painting problem. The results from the simulation experiments verify our hypotheses – the proposed pre-sequencing methodology is able build sizable paint blocks without sacrificing sequence control, while the conventional substitution method is not.

In addition to these results, the simulation experiments suggest a completely unexpected phenomenon. It seems that it might be possible to use pre-sequencing to actually enhance sequence control capabilities. The simulation output for the pre-sequencing experiment indicates that the AS/RS requirements (i.e., the size of the AS/RS system) increase far less than expected given the disturbance caused by the creation of paint blocks. Also, the substitution Block Painting methodology – which generates paint blocks dynamically using an algorithm similar to the static pre-sequencing methodology – results in no additional AS/RS requirements when small search windows are used. The following section explains the reasons for this behavior. The subsequent section gives an example of how we can apply the underlying theory to improve sequence control.

6.1 Controlling Sequence Disruption

Recall, from Chapter 3, the flow of the Wixom ILVS system. The output of two body shops flows into a single paint shop, composed of two sequential phases. Substitution takes place just after the Phase-1 paint shop and again after the Phase-2 paint shop. From there, vehicles enter the AS/RS facility and leave 98% in sequence. When using pre-sequencing, this system can be thought of as containing the following logical components:

- Pre-sequencing mechanism
- Body and paint shop subsystem
- Post-paint substitution station
- Automated Storage and Retrieval System

Each of these sub-systems either adds to or counters distortion in the system. The pre-sequencing mechanism adds some distortion to the ILVS system, if used to create paint blocks or to satisfy other body or paint shop needs. As this chapter demonstrates, however, it can also help counter downstream distortion. The body and paint shop subsystem produces the bulk of the sequence disorder. The last two components – the post-paint substitution station and the AS/RS – act to restore order to the sequence. In the following discussion, we examine the effect of each of the four system components. First, we analyze the sequence distortion created in the body and paint shop subsystem. Then, we discuss the sequence restoration capabilities of the post-paint substitution station and the AS/RS. Finally, we examine the potential of the pre-sequencing stage to help counter sequence distortion.

6.1.1 Body and Paint Shop Subsystem

Figure 6-1 shows the sequence distortion in the vehicles leaving the Phase-2 paint shop. The numbers along the x-axis represent distances out-of-sequence. The positive numbers denote late cars, while the negative numbers denote early cars. The values along the y-axis report the number of cars that are out-of-sequence for each of the distance values along the x-axis. To show the accumulated distortion caused by all three components (the body shop and both phases of paint), this example ignores the effect of the first substitution station by using the modified base case experiment (Section 5.3.4).

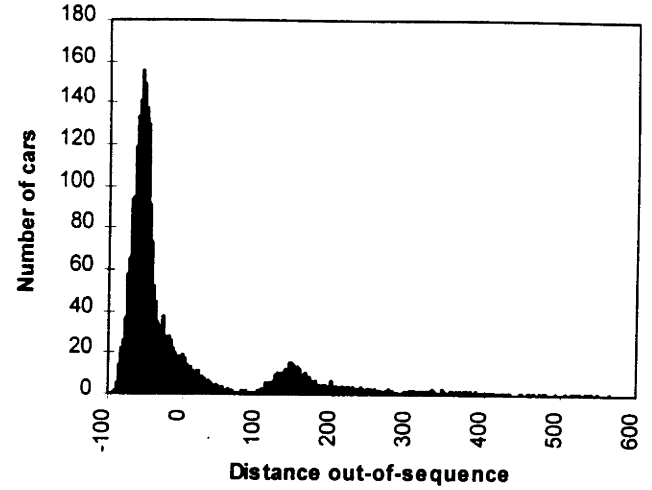


Figure 6-1: The distance-out-of-sequence distribution for the body/paint shop subsystem with the first substitution station deactivated

Of the three body and paint shop subsystem components, the Phase-2 paint shop contributes the most significant amount of sequence distortion. In relative terms, the body shop and the Phase-1 paint shop add little or no sequence distortion to the body and paint shop subsystem. The next two graphs provide clear evidence to support this conclusion. Figure 6-2 shows the sequence disruption occurring in the body and paint shop subsystem for the original base case experiment. This example, unlike the previous one, includes the effect of the first substitution station. Figure 6-3 shows the sequence disruption occurring only in the Phase-2 paint shop. The fact that all three of these figures are so similar suggests that Phase-2 dominates the disruption in the body and paint shop subsystem. With or without the first substitution station, the sequence entering Phase-2 is essentially undistorted compared to the sequence exiting Phase-2. The congruence in the output of the original and modified base case experiments in Chapter 5 verifies this conclusion.

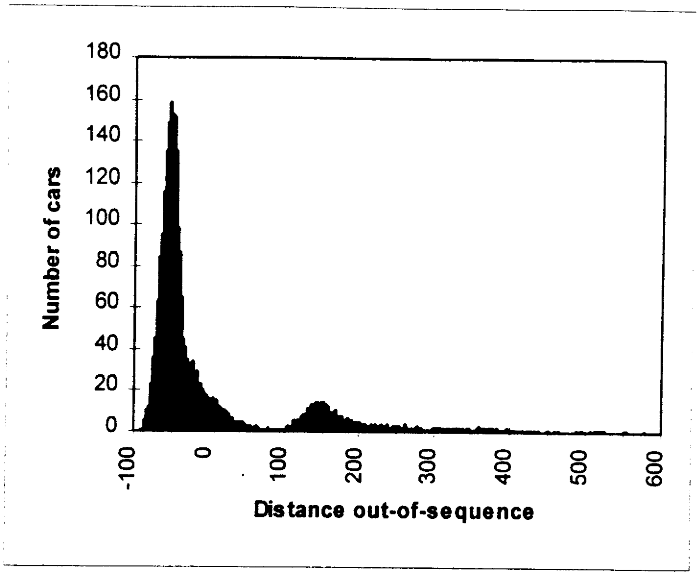


Figure 6-2: The distance-out-of-sequence distribution for the body/paint shop subsystem in the base case

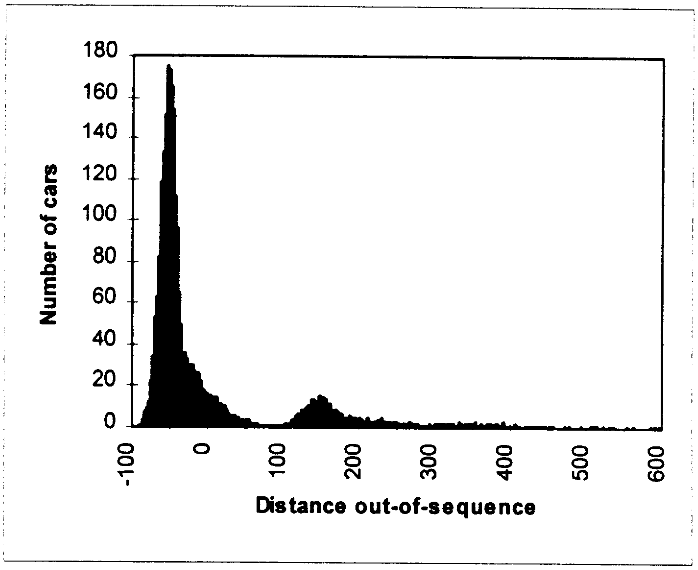


Figure 6-3: The distance-out-of-sequence distribution for the Phase-2 paint shop

The bi-modal shape, so prominent in each of these figures, reflects the fundamental nature of the paint application process. All vehicles must pass an inspection for paint quality. A percentage of the painted vehicles need repainting and must return to the start of the painting cycle. The first mode contains the cars that make it through the painting process in one pass, while the second mode depicts the cars that loop back. Notice that the majority of vehicles are just a little early. When a vehicle becomes late, either by being pulled off-line or by recycling through the system, each of the vehicles that bypass it become one unit early. The net effect is a small shift in the distribution to the early side.

6.1.2 Post-Paint Substitution Station

The system processes 82 distinct types of painted Town Car and Continental car bodies. Each of these painted car bodies occurs at a certain frequency. For example, in the first data set of 6560 cars, 728 are white Town Cars with no moon-roof. At 11.9%, this particular painted-body is a very high-runner. In this same data, the painted body types of 982 vehicles occur fewer than fifty times in the blend. These cars are low-runners. Chapter 2 discussed the concept of painted-body complexity, and Appendix B provides a breakdown of the data according to painted-body complexity. Assuming that the high-running cars are uniformly distributed throughout the blend, they will be relatively easy to substitute for. Even if they become very out-of-sequence, the substitution effect will attenuate their net distortion. In contrast, substitution does little to help the low-running vehicles, which become significantly out-of-sequence.

Figure 6-4 shows the post-substitution distribution for the high-running vehicle type. This distribution resembles the pre-substitution distribution (Figure 6-3) in shape, but is collapsed in scale. Figure 6-5, on the other hand, depicts the post-substitution distribution for the low-running vehicles. As expected, the distribution has approximately the same shape and scale as the pre-substitution distribution.

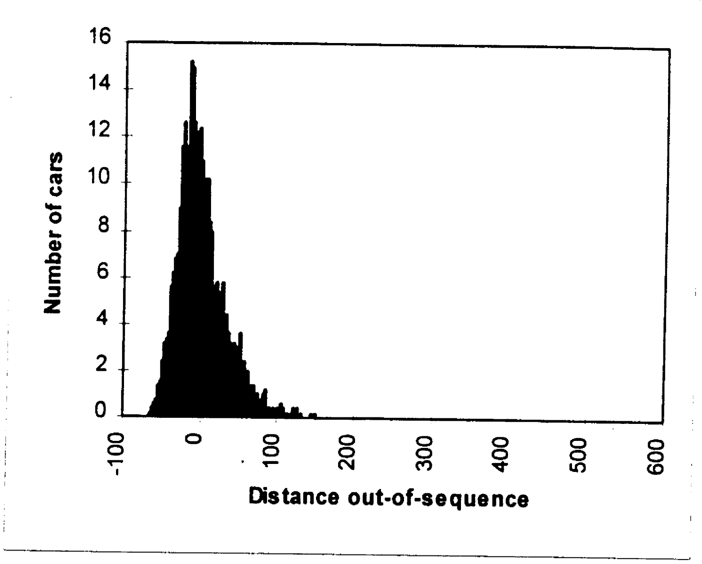


Figure 6-4: The post-substitution distance-out-of-sequence distribution; high-running vehicle type

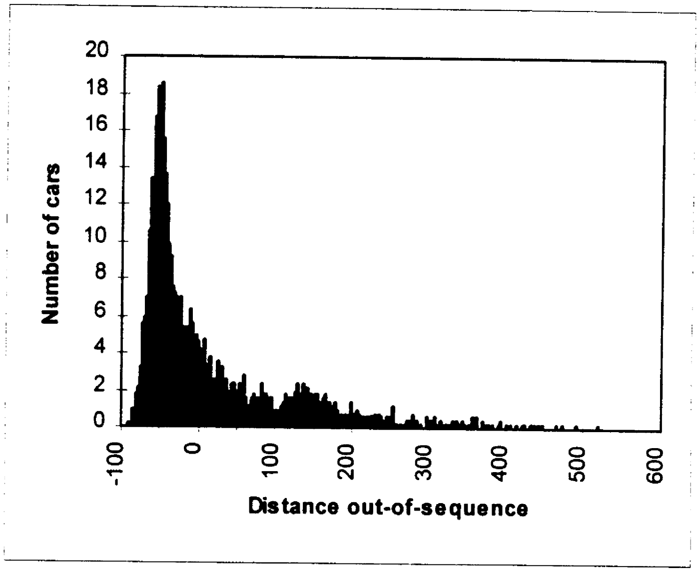


Figure 6-5: The post-substitution distance-out-of-sequence distribution; low-running vehicle types

6.1.3 Automated Storage and Retrieval System

The AS/RS re-sequences the painted car bodies as they leave the post-paint substitution station. Chapter 2 described the purpose and physical implementation of the AS/RS. In the ideal sense, the AS/RS is filled to capacity and the vehicle input rate is precisely the same as the vehicle output rate. Under these conditions, an AS/RS of size X is capable of re-sequencing all vehicles that are less than X units late. Figure 6-6 shows a distance-out-of-sequence histogram for the post-substitution vehicle stream entering the AS/RS in the base case experiment. In this example, 98% of the vehicles are less than 165 units late. Accordingly, an ideal AS/RS of size 165 is needed to re-sequence 98% of the vehicles. As discussed in Chapter 5, the ideal AS/RS size needed to restore to 98% in sequence serves as a useful metric for evaluating sequence distortion. In practice, an AS/RS is not ideal; it is never filled to capacity since a certain percentage of the AS/RS space is used to smooth out variability in the input and output rates. The Wixom AS/RS, which serves the re-sequencing needs of both the Town Car/Continental and Mark VIII National Blends, also contains additional capacity to protect against down-time.

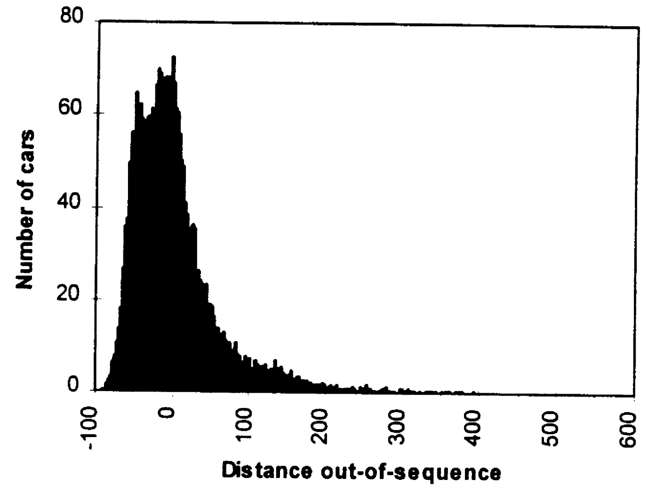


Figure 6-6: The post-substitution distance-out-of-sequence distribution; all vehicle types (AS/RS input)

Comparing the distributions in Figure 6-2 and Figure 6-6, we can see that the substitution mechanism drastically reduces the AS/RS requirements. The pre-substitution distribution demands a 351-unit AS/RS to re-sequence 98% of the vehicles, while the post-substitution distribution needs only a 165-unit AS/RS. Figures 6-4 and 6-5 demonstrate that the high-running vehicles are mainly responsible for this effect.

6.1.4 Pre-sequencing Mechanism

The results of the substitution and pre-sequencing experiments in Chapter 5 suggest the possibility of using pre-sequencing to improve sequence control. Even though both methodologies introduce significant sequence distortion into the system when they create paint blocks, neither the pre-sequencing method nor the substitution method with the smallest search window leads to a significant increase in AS/RS requirements. Aside from certain constraints, both methods employ the same algorithm to build paint blocks. This algorithm tends to pull-in, or make early, lower-running vehicles more so than higher-running vehicles. We believe this to be responsible for the lower-than-expected AS/RS requirements.

A sequence control improvement effort attempts to either minimize the AR/RS size needed to restore sequence to a constant percentage (say 98%) of vehicles or maximize the percentage of vehicles that an AS/RS of constant size can re-sequence. Success in one area generally implies some success in the other. Figure 6-6 shows a distance-out-of-sequence histogram for a vehicle stream entering the AS/RS. In this example, 2% of the vehicles are 165 or more units late. Pre-sequencing could focus on making these late vehicles a little earlier, thereby increasing the percentage of vehicles re-sequenced for the current AS/RS size. Alternatively, the pre-sequencing mechanism could direct its attention on the 98% within the AS/RS capabilities. Each of these vehicles could be made a bit earlier to reduce the AS/RS size requirements.

The basic strategy of pre-sequencing is to cater to those vehicles that are likely to become late. To accomplish this, we must take the following steps:

- Move the lower-running vehicles earlier than the higher-running vehicles, since they are more likely to end up late (see the discussion on the post-paint substitution station).
- Exercise care not to make too many cars too early. A balancing effect will cause a proportional number of cars to become late, thereby increasing the AS/RS requirements.

The next section shows, through simulation, how pre-sequencing can help reduce AS/RS requirements.

6.2 Improving Sequence Control

The previous section showed that low-running vehicles benefit very little from substitution. Therefore, of the 2% of the vehicles not making the AS/RS window (those that are 165 or more units late in figure 6-6), a disproportionately high fraction should be low-runners. An examination of the vehicle sequence represented in Figure 6-6 confirms this hypothesis. Even though low-runners make up only 14% of the data set, they comprise approximately 50% of the vehicles exceeding the AS/RS capabilities. By pre-scheduling these vehicles, a greater percentage should make the re-sequencing window.

The challenge is to do so without bypassing too many vehicles. Even though a high proportion of the late cars are low runners, the majority of the all the cars, including the low-runners, are not late. In fact, the distributions in Figures 6-1, 6-2, and 6-3 show that the majority of the cars are a little early. In other words, of the cars that we pre-sequence, only a small percentage will actually offset the vehicles that tend to be late. The rest become even earlier than they would have before. If we make too many cars too early, the results can be detrimental. For example, if a car becomes 50 units earlier than it would have been without pre-sequencing, 50 other cars become one unit later than before. Clearly, as the number of excessively early cars increases, the late cars become even later and the AS/RS requirements increase.

Table 6-1 shows the pre-sequencing approach that led to the desired effect. The first column indicates which cars we chose for pre-scheduling, while the values in the second column specify how far we pre-scheduled these cars. For example, as shown by the first row, we pre-schedule by 100 units the lowest running cars, whose painted-body types comprise 0.25% or less of the Data Set-1 blend. We arrived upon the ranges in the first column and the associated values in the second column by trial and error.

Total occurrence of a painted-body type in the Data Set	**Pre-sequence Distance**
0.25% or less	100
0.26% to 0.5%	75
0.51% to 0.75%	50
0.76% to 1.0%	25
more than 1.0%	0

Table 6-1: The pre-sequencing approach used to improve sequence control

Table 6-2 shows the AS/RS requirements without pre-sequencing. The base case experiment in Chapter 5 serves as the base case for this exercise as well. The values in the first column, which show the AS/RS requirements for 98% in-sequence performance, are identical to those in Table 4-1. The values in the second column, which indicate the AS/RS requirements for 99% in-sequence performance, permit us to compare the situation before and after pre-scheduling.

Trial #	AS/RS Size for 98%	AS/RS Size for 99%
1	157	191
2	156	199
3	171	223
4	168	229
5	175	214

Table 6-2: The AS/RS requirements without pre-sequencing (base case)

Table 6-3 displays the AS/RS requirements after we apply the pre-sequencing approach shown in Table 6-1. The average AS/RS size needed for 98% in-sequence performance drops from 166.4 to 158.4, while the AS/RS size needed for 99% in-sequence performance drops from 211.2 to 196.0.

Trial #	AS/RS Size for 98%	AS/RS Size for 99%
1	154	193
2	146	184
3	165	202
4	163	203
5	164	198

Table 6-3: The AS/RS requirements with pre-sequencing

Unlike the pre-sequencing we used in Chapter 5 to implement Block Painting, the pre-sequencing we use in this experiment structurally resembles the sequencing of the base case. In Chapter 5, to protect the paint blocks from being substituted away, we deactivated the first substitution station for the pre-sequencing experiment. Here, we are using pre-sequencing to improve sequence control, not to create and propagate paint blocks. Therefore, we can retain the substitution station. Also, unlike the pre-sequencing used for Block Painting, we can satisfy the body shop mix constraints simply by forcing the new sequence into a three-to-one rotation. Doing so has no measurable impact on our pre-scheduling objectives. Thus, the pre-sequencing we discuss here enables improved sequence control at essentially no additional cost.

Chapter 7

IMPLEMENTATION CONSIDERATIONS

Chapter 3 introduced the concept of pre-sequencing, while Chapter 5 examined the applicability of the concept to Block Painting. This chapter considers the implemention of a pre-sequencing approach for improving Block Painting. The first section identifies simple adjustments needed in the idealized ILVS environment. It then considers the special modifications required by the ILVS system at Wixom. The second section proposes a strategy for implementing these changes.

7.1 Physical Implementation

This section describes the modifications we must make to the ILVS system to implement our new approach to Block Painting. When considering these changes, we distinguish between two types of ILVS contexts: the ideal ILVS environment, and the Wixom ILVS environment. Both require relatively inexpensive modification to the scheduling and vehicle identification systems, while the second requires additional investment in hardware.

7.1.1 Implementation at the Ideal ILVS Plant

In the ideal ILVS environment, the implementation of Block Painting by pre-sequencing requires only the following minor changes:

- We must adapt the scheduling system to produce a modified National Blend sequence as well as the regular National Blend sequence. The modified sequence contains the paint blocks and will be used only in the body and paint shops.
- Most ILVS sequence control mechanisms require knowledge of a vehicle's sequence number. We must alter the AVS/AVI system, which provides this information, to report the appropriate sequence number. For processes in the body or paint shop, the system must provide the modified sequence number, and for those after the paint shop, such as the second substitution station and the AS/RS, it must report the original National Blend sequence number.

- Since the first substitution station is free to assign new paint colors to vehicles, we must deactivate it. Chapters 5 and 6 showed that the effect of the first substitution station on sequence control is negligible.
- Chapter 3 presented the concept of block protection, while the simulation output in Chapter 5 provided quantitative evidence of its importance. The AVS/AVI system must therefore be used at the re-run merge point in the paint shop to protect paint blocks from being broken.

Most of these changes call for simple adjustments to the programming of the scheduling and AVS/AVI computer systems. The only change that could require the addition of any hardware is the last one – the implementation of block protection. Since the rejected vehicles cannot immediately merge back into the enamel application process, they might require some addition surge space during their wait.

7.1.2 Implementation at Wixom

Chapter 3 compared the Wixom ILVS system to the ideal ILVS environment. In the ideal case, the body and paint shops impose no constraints on the National Blend sequence. At Wixom, however, the vehicles must enter the main body shop in a precise three-to-one rotation of Town Cars to Continentals. Moreover, because Wixom caters to two National Blends, the merging pattern of the Mark VIII sequence further complicates the situation. Also, the use of parallel processes at Wixom causes a shuffling of the vehicles. When operating in this environment, the pre-sequencing Block Painting methodology will not be able to create and maintain adequate paint blocks.

In spite of these difficulties, the pre-sequencing approach still has merit. Consider a Block Painting approach that uses a large sortation buffer to create paint blocks. This buffer sits right before the Phase-2 paint shop – the same location in which the substitution methodology creates paint blocks. The size of this buffer depends on the dispersion of like colors in the incoming sequence. A sequence with like colors spaced far apart requires a larger buffer than a sequence that spaces like colors close together. For our purposes, this “brute force” approach is impractical. Since like colors tend to be highly dispersed in the National Blend, the required bank size would be very large – taking up too much space, costing too much, and adding too much to the vehicle flow time. However, by using pre-sequencing to create a blocked sequence, which we subsequently force into the required three-to-one rotation, we minimally disperse like-colored vehicles. The accumulation buffer needed to recreate the paint blocks in this case would be much smaller than in the brute force scenario.

Figure 7-1 describes this approach. Both the Town Car/Continental National Blend and the Mark VIII National Blend are pre-sequenced, but are merged together in the normal eight-to-one fashion upon entering the paint shop. After the Phase-1 paint shop, the vehicles enter the accumulator and exit in blocks of like color.

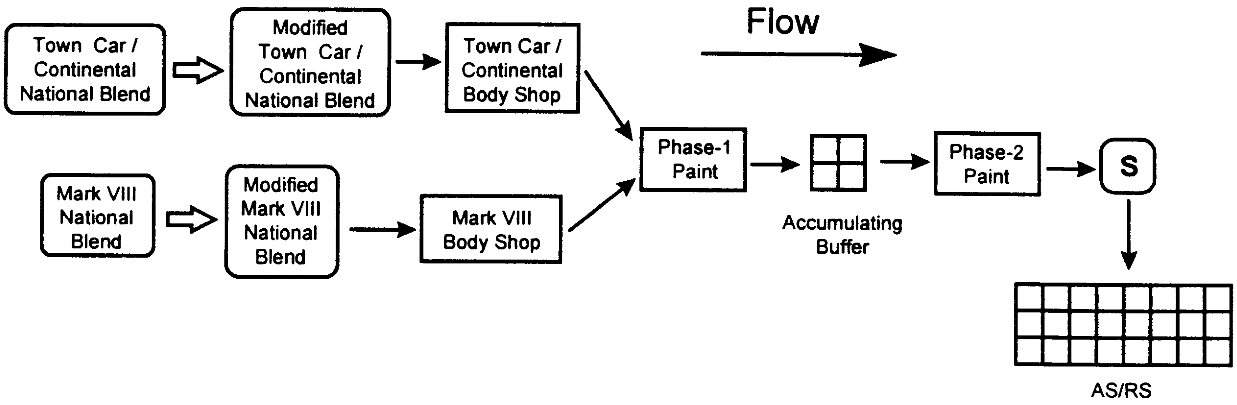


Figure 7-1: Pre-sequencing with a small accumulating buffer

If successfully implemented, this approach would deliver paint blocks to the entrance of the Phase-2 paint shop. Two additional challenges remain in propagating the paint blocks to the enamel booths. First, the system currently does not maintain sequence (and consequently paint blocks) through the sand and wash operation – a parallel process that prepares primed vehicles for paint application. Obviously, this must be rectified. Second, Wixom uses a dual paint booth system. At present, the system is capable of sending a maximum of three cars in succession to either booth. Thus, upon reaching the enamel booths, a ten-car paint block would separate into two five-car paint blocks. For Block Painting to work properly, the system must be capable of sending an entire paint block to either booth. The plant might accomplish this by installing an appropriate buffering mechanism at a location prior to the dual booth system.

7.2 Implementation Strategy

We use pre-sequencing to create tailored sequences for distinct areas of the assembly plant in order to meet the specialized needs of these areas. Our ability to do so hinges on two factors: (i) the degree to which the sequences in these areas are de-coupled, and (ii) the magnitude of any superfluous constraints that these sequences must satisfy. We demonstrated in Chapter 5 that the AS/RS effectively de-couples the body and paint shops from the trim and chassis shops. We can therefore create separate sequences for these sections of the plant. Since, in the ideal ILVS environment, the body and paint shops do not impose any special sequence requirements, the body and paint shop sequence can easily satisfy the paint shop's paint blocking needs.

In the Wixom environment, however, the body shop and the Phase-1 paint shop require that the sequence conform to a designated rotation of vehicles (as discussed in Chapter 3). In a sense, the body shop and the Phase-1 paint shop impede our attempt to propagate paint blocks all the way to Phase-2. To meet the paint blocking needs of Phase 2; we have the following two options: (i) we can de-couple the Phase-1 and Phase-2 sequences (as per our suggestion in Section 7.1.2 of installing a small accumulating buffer), or (ii) we can eliminate the body shop and Phase-1 constraints altogether, thereby moving toward the ideal ILVS environment.

How do we decide which option to pursue? Our implementation strategy must account for a variety of factors, including:

- **Plant characteristics:**
  - Does the plant have enough space for an accumulation buffer?
  - Can the plant afford to increase the work-in-process time?
  - What is the nature of the resource limitations that cause the upstream sequence constraints?
- **Implementation costs:**
  - What are the installation and maintenance costs of the accumulator hardware?

  - What are the costs of removing sequence constraints (additional manpower, machinery, etc.)?

- **Future Outlook:**
  - To what degree will removing constraints (i.e., moving toward the ideal implementation) improve the quality and reliability of the process/product?
  - Are there process/technology improvements in the pipeline (e.g., increased automation) that could incidentally remove some of the constraints?

An objective of every ILVS plant should be to reduce or eliminate body and paint shop sequence constraints. Our research has shown that the resulting pre-sequencing capabilities offer significant gains in terms of Block Painting performance and sequence control. In the near term, however, it might be more cost-effective to manage these constraints, rather than removing them outright, while still reaping many of the same benefits.

Chapter 8

CONCLUSIONS

This research has demonstrated the compatibility of In-Line Vehicle Sequencing and Block Painting. Through simulation, the thesis first explored the capabilities of conventional substitution-based Block Painting – determining that the methodology produces modest gains in average block size. Next, the thesis investigated the application of pre-sequencing, in the ILVS environment, to Block Painting. The analysis revealed the potential for significant improvements in Block Painting performance without compromising the effectiveness of ILVS sequence control. Finally, the thesis extended the pre-sequencing concept to improve sequence control capabilities. Our research findings and recommendations for further research fall into three categories: (i) Block Painting, (ii) opportunistic ILVS scheduling (i.e., pre-sequencing), and (iii) plant and process characteristics.

8.1 Research Findings

Using simulation modeling and analysis, we arrived at the following conclusions.

Block Painting

The substitution method with a small search window should lead to significant savings at Wixom. The simulation output in Section 5.3.2 indicated that for a search window of value 75, we can expect, with no increase in AS/RS requirements, an increase in average block size from 1.23 to 1.94 – equivalent to an annual savings of $902,000 (assuming an annual volume of 200,000 cars). For a search window of value 150, the block size increases to 2.15 – equivalent to an annual savings of $1,060,000 – with a 5% increase in AS/RS requirements. For larger search window sizes, the AS/RS requirements increase linearly, while the average block size reaches an asymptotic level. For example, a search window of value 1200 results in an average block size of 2.63, but leads to a 370% increase in AS/RS requirements. This resulting annual savings amount to $1,320,000 – just $419,000 more than the savings produced by the smallest search window.

The pre-sequencing approach consistently produces large paint blocks. Section 5.3.3 reported an increase from 1.23 to 3.6 in average block size – equivalent to an annual savings of $1,670,000 – with a 7% increase in the required AS/RS size. Note that this methodology depends only on the distribution of colors in the blend. Accordingly, the blocking capability would remain unchanged should the number of body configurations (the BIW complexity) increase. The capability of the substitution methodology, on the other hand, hinges directly on the BIW complexity. Thus, the Wixom results for the substitution methodology (given above) are promising because the BIW complexity is very low.

Block protection is extremely important. Sections 5.3.2 and 5.3.3 demonstrated the effect of not implementing block protection. Recall that block protection simply prevents a vehicle, coming out of repair, from interrupting a paint block. We require block protection regardless of which Block Painting methodology we choose. With the pre-sequencing methodology, for instance, the elimination of block protection reduces the average block size at the paint booth from 3.54 to 2.72.

A new Block Painting evaluation metric would accurately direct cost-reduction efforts. Chapter 4 demonstrated that the paint purge costs at Wixom vary considerably across paint colors. The cost of the most expensive color exceeds the cost of the least expensive color by a factor of 3.1. Since Block Painting aims to reduce total material usage cost, Section 4.2 proposed the use of a cost-weighted average block size metric instead of the conventional average block size metric. Given a choice between two Block Painting schemes that produce identical average block sizes, the new evaluation metric should identify the one leading to the greatest cost savings.

Opportunistic ILVS Scheduling

The first substitution station adds little value. Chapter 5 demonstrated that the AS/RS requirements increase by a mere 2% when we deactivate the first substitution station. Chapter 6 explained this behavior by showing that the sequence distortion occurring after the first substitution station (in the Phase-2 paint shop) far outweighs the sequence distortion occurring before the first substitution station (in the body shop and the Phase-1 paint shop). This outcome is advantageous to our pre-sequencing Block Painting methodology, since the methodology requires the deactivation of the first substitution station.

We can improve sequence control by pre-scheduling a portion of the low-running vehicles. Chapter 6 explained why the post-paint substitution mechanism re-sequences high-running vehicles more effectively than low-running vehicles. We used this insight to develop a pre-sequencing scheme that pre-scheduled the lowest-running vehicles earliest. This design produced a 5% reduction in AS/RS size, assuming the standard 98% in-sequence goal, and a 9% reduction in AS/RS size, assuming 99% in-sequence performance.

The following observations about this technique are worth noting. First, we might be able to improve upon the results since our approach determined the pre-scheduling parameters by trial-and-error. Second, the technique would not be of value in an environment with a high degree of painted-body complexity – a setting in which all of the vehicles would effectively be low-runners. Finally, we can implement this technique at Wixom without removing the three-to-one mix constraints in the body and paint shops. In this pre-sequencing approach, we are concerned only with the pre-scheduling of low-running vehicles, not the propagation of paint blocks.

Plant and Process Characteristics

We can compensate for body and paint shop sequence constraints, but at a cost. The body shop and the Phase-1 paint shop at Wixom impose vehicle mix constraints on the National Blend sequence. Consequently, we are unable to pre-sequence large paint blocks without eliminating or circumventing these constraints. Chapter 7 offered a solution that would allow for a de-coupling of the Phase-1 and Phase-2 paint shops, effectively meeting the constraints and creating blocks at the same time. Although we expect our pre-sequencing approach to minimize the size of this de-coupling buffer, the solution would incur additional capital investment and vehicle flow time costs.

Paint blocks overload the tri-coat upgrade operations. Although not explicitly demonstrated in the thesis, our preliminary simulation runs exhibited marked degradation in system throughput for paint-blocked sequences. Further investigation revealed that the tri-coat upgrade operations were responsible for this effect. Just as we altered our simulation modules to compensate for these capacity limitations, the plant would have to adjust the actual system to accommodate Block Painting.

8.2 Recommendations for Further Research

To support our conclusions and to explore other areas for improvement, future investigations might address the following topics.

Block Painting

Optimize the Block Painting parameters. In this thesis, we have demonstrated the viability of our proposed concepts by formulating "existence proofs". We did not attempt to optimize the key parameters. For both the substitution and pre-sequencing approaches to Block Painting, we selected search window and target block sizes that resulted in acceptable paint block sizes and sequence distortion levels. Our pre-sequencing approach might benefit from a careful sensitivity analysis to determine improved values for these parameters.

Investigate the implementation of pre-sequencing at Wixom. Our analysis quantified the benefits of using pre-sequencing to achieve Block Painting in the ideal ILVS environment. Although Wixom is not an ideal ILVS environment (no plant is), we believe that the plant could implement pre-sequencing by installing an accumulating buffer between the Phase-1 and Phase-2 paint shops (see Chapter 7). Additional simulation and analysis might address the following issues. First, what bank size does the system require to generate the same block sizes as the ideal pre-sequencing methodology? Is this bank significantly smaller than the one required by a brute-force implementation (i.e., one without pre-sequencing)? Second, since the substitution methodology offers savings without additional hardware or flow time, are the incremental savings generated by the pre-sequencing methodology sufficient to justify the cost of the buffer and the increased flow time?

Accommodate multiple paint booths. For simplicity, our simulation experiments assumed a single paint booth. However, most of Ford's assembly plants use more than one paint booth. As we described in Chapter 5, unless the plant puts the proper measures in place, multiple paint booths will have the undesirable effect of separating paint blocks. This disruption will occur regardless of which Block Painting methodology we implement.

Opportunistic ILVS Scheduling

Optimize the pre-scheduling parameters for sequence control improvement. We demonstrated in Chapter 6 (an "existence proof") the merit of pre-sequencing to improve sequence control. Again, we did not optimize the key parameters. A careful sensitivity analysis would reveal not only the most appropriate vehicles to pre-schedule, but also how early to pre-schedule them. We believe that significant additional reductions in AS/RS requirements are still possible.

Investigate other opportunities for pre-sequencing. This thesis applied the concept of pre-sequencing to two separate problems: Block Painting and sequence control. In both cases, we used pre-sequencing to accommodate the foreseeable disruptions, effectively alleviating the system from having to deal with them downstream. Two additional topics for further research become apparent. First, how do we combine multiple pre-sequencing applications? That is, can we use pre-sequencing both to create paint blocks and to improve sequence control? Second, what other applications are suited for pre-sequencing? Additional opportunities might exist in the body shop or in other areas of the paint shop. Only by ascertaining the full range of pre-sequencing possibilities can we hope to maximize the utility of the pre-sequencing concept.

Plant and Process Characteristics

Analyze the extent to which a failure to maintain vehicle sequence through parallel structures affects paint blocks and sequence control. The ideal ILVS implementation ensures that parallel processes maintain vehicle sequence. The system admits cars into these parallel processes in an alternating fashion and removes them in the same manner. In practice, an ILVS system might instead follow a "first-available" policy to avoid compromising system throughput. The effect of such a policy on paint blocks and sequence control is not fully understood. Our intuition tells us that such shuffling has little or no effect on overall sequence control, but can be detrimental to paint blocks. The question remains, how detrimental? Can we correlate the statistical variation in the cycle time of a parallel process to the impact the process has on paint blocks? Gaining an understanding of these dynamics would help focus process improvement efforts.

Consider removing constraints and non-conformities in the body and paint shops. We devoted much of this thesis to the differences between the ideal ILVS environment and practical ILVS environments. The ideal ILVS environment facilitates and complements the concept of pre-sequencing. It permits the system to accommodate the needs of the body and paint areas without having to first satisfy a variety of extraneous constraints. Without these constraints, we can implement initiatives such as Block Painting at a minimal cost. Further research should thus focus on identifying and eliminating the most critical constraints.

8.3 Broader Implications

Although this thesis has investigated a specific application in the automotive industry, the concepts and overall approach we have examined potentially have broader applicability. These same ideas apply to multi-staged production processes whenever the "optimal" sequencing within the various stages differ. Rather than setting the flow sequence to optimize one stage (e.g., final assembly in our setting), we could adopt a broader system-wide perspective, using a pre-sequencing approach that attempts to balance the needs of the various stages, or through appropriate decoupling, to achieve near optimal sequencing characteristics. The implementation of this approach will differ by context (e.g., some other system will replace the AS/RS facility), but the basic concepts might be much the same.

Appendix A

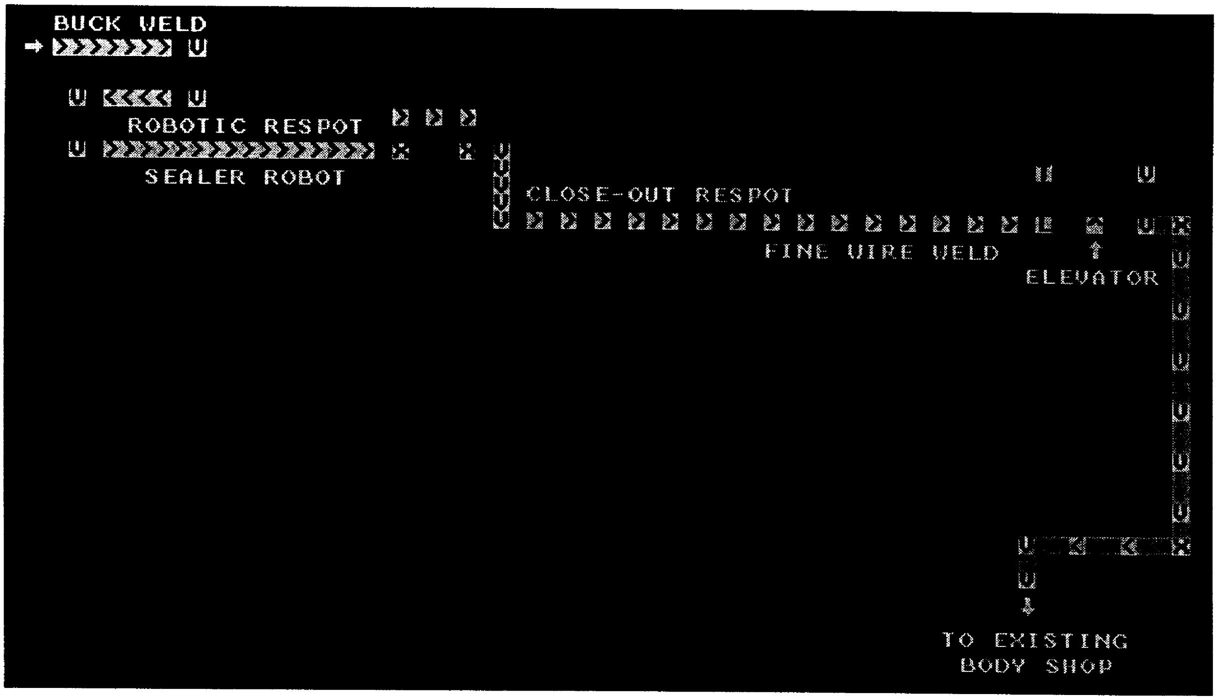
SIMULATION COMPONENTS

This appendix presents each of the simulation modules, helper applications, and analysis tools used to run the simulation.

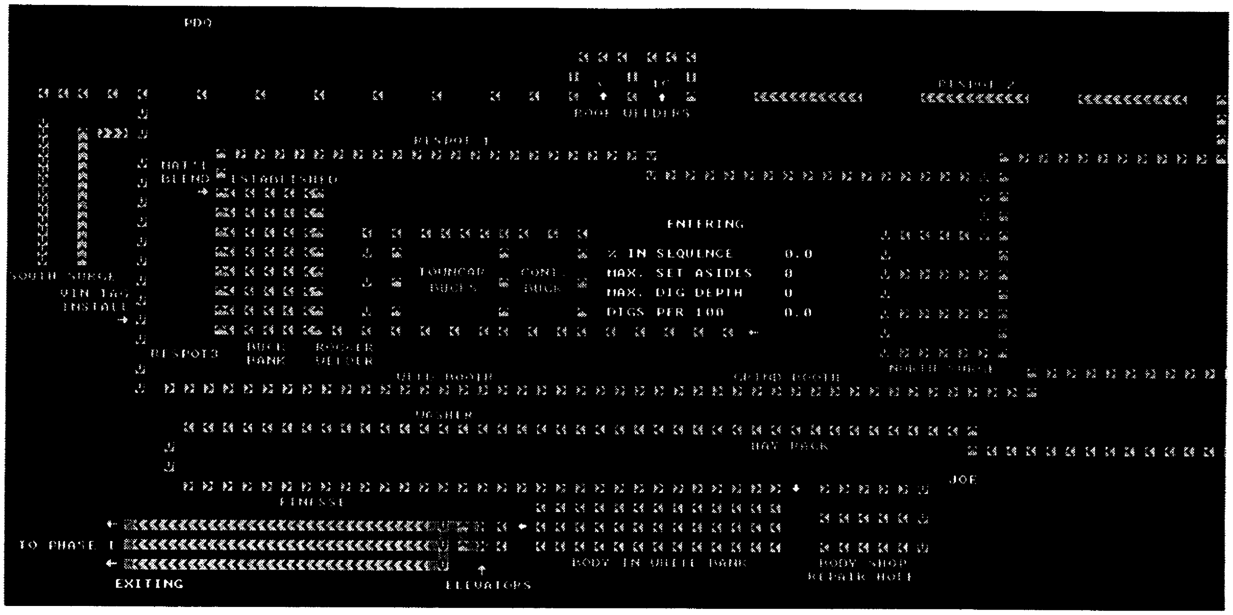
Simulation Modules

As described in Chapter 5, an engineering consulting firm (CKGP) developed a set of simulation modules for the Wixom ILVS implementation. We use the following modules in our simulation: the Mark VIII body shop, the Town Car / Continental body shop, the Phase-1 paint shop, and the Phase-2 paint shop. We provide a graphical representation for each module.

Mark VIII body shop



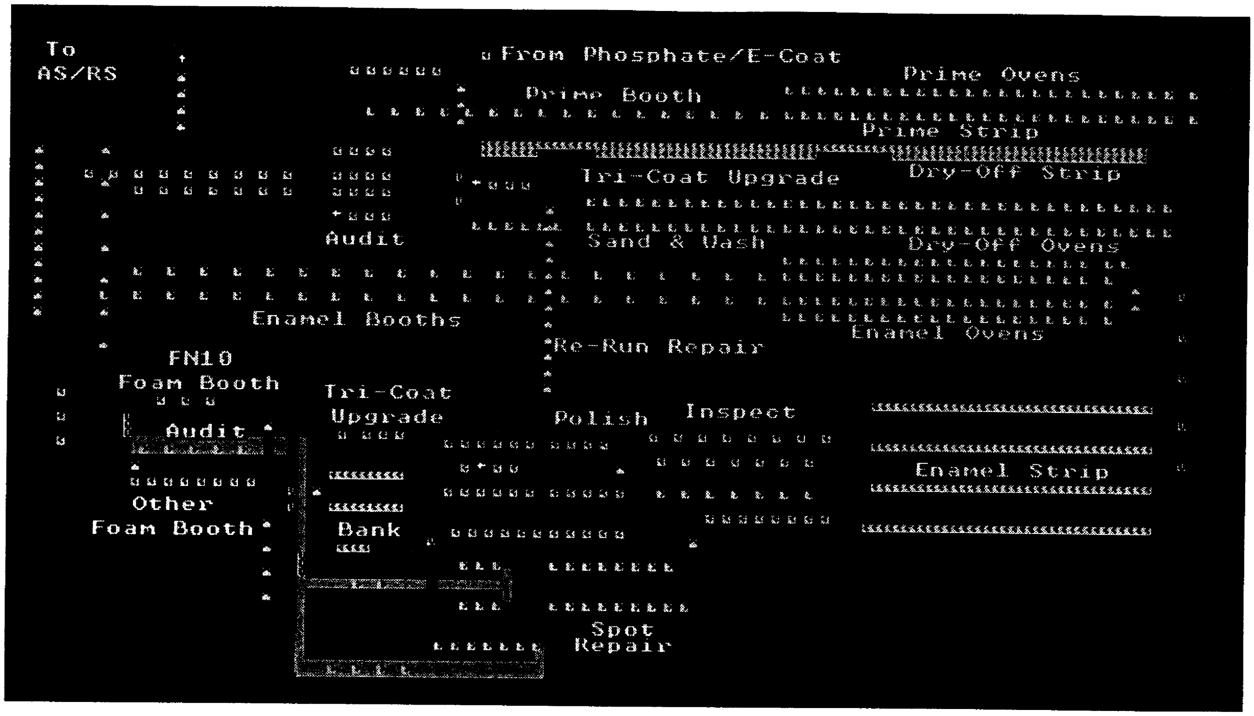
Town Car / Continental body shop



% IN SEQUENCE 0.0
MAX. SET ASIDES 0
MAX. DIG DEPTH 0
DIGS PER 100 0.0

Phase-1 paint shop

Phase-2 paint shop



Helper Applications

The simulation model relies on the following helper applications:

Pre-sequencing Mechanism

We use the pre-sequencing mechanism to provide the simulation model with large paint blocks in the initial vehicle sequence. The pre-sequencing mechanism requires two parameters: (1) the target block size, and (2) the search window size.

Algorithm

```
; Input:    Target Block Size
            Search Window Size

; Define:   Number In Block
            Blend Number
            Current Color
            Index
```

```
Index = 1

While unmarked cars remain in the blend Do Loop1

    Blend Number = the sequence number of the first unmarked vehicle in the blend
    Current Color = the color of the first unmarked vehicle
    Number In Block = 0

    Do Loop2  Until    (all the cars in the blend are marked) or
                       (Number In Block = Target Block Size)
        If (Blend Number - Index) > Search Window Size then
            Exit Loop2
        Else
            Add this vehicle to our new sequence.  Its modified sequence number is Index and its
                original sequence number is Blend Number
        End If
        Mark the vehicle as being removed
        Increment Index
        Increment Number In Block
        Blend Number = the next unmarked vehicle of the same color as Current Color
    End Loop2

End Loop1
```

Substitution Station #1 (normal operation)

The first substitution station (normal operation) swaps the identification numbers of vehicles with the same body-in-white complexity to restore vehicle sequence before entering the paint shop.

Substitution Station #1 (paint-blocking operation)

The first substitution station (paint-blocking operation) swaps the identification numbers of vehicles with the same body-in-white complexity both to restore vehicle sequence and to create paint blocks before entering the paint shop. This mechanism requires the same two parameters as the pre-sequencing mechanism: (1) the target block size, and (2) the search window size.

Substitution Station #2

The second substitution station swaps the identification numbers of vehicles with the same painted-body complexity to restore vehicle sequence after leaving the paint shop.

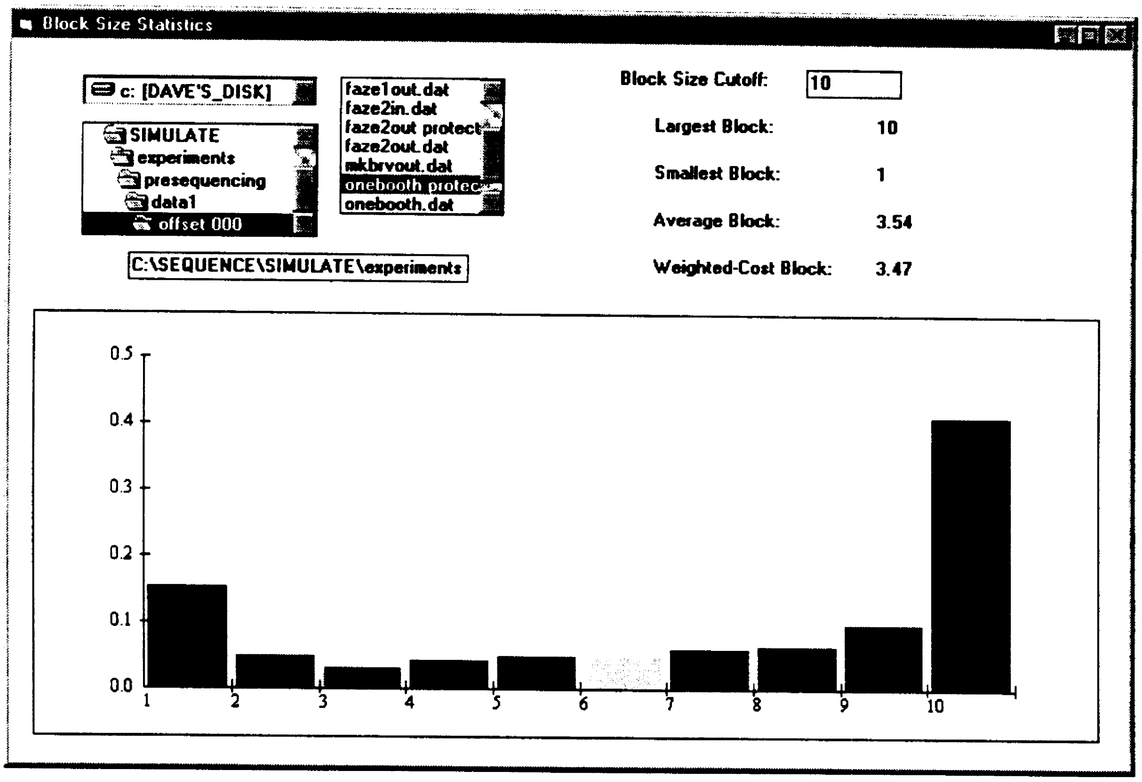
Analysis Tools

AS/RS tool

The AS/RS tool accepts an input stream and a parameter representing the size of an ideal AS/RS and then determines the percentage of vehicles in the output stream that are in-sequence.

Paint block size tool

The paint block size tool determines the average paint block size in the input stream. In addition, it displays a histogram profile of the paint blocks in the input stream.



C:\SEQUENCE\SIMULATE\experiments

Block Size Cutoff: 10

Largest Block: 10

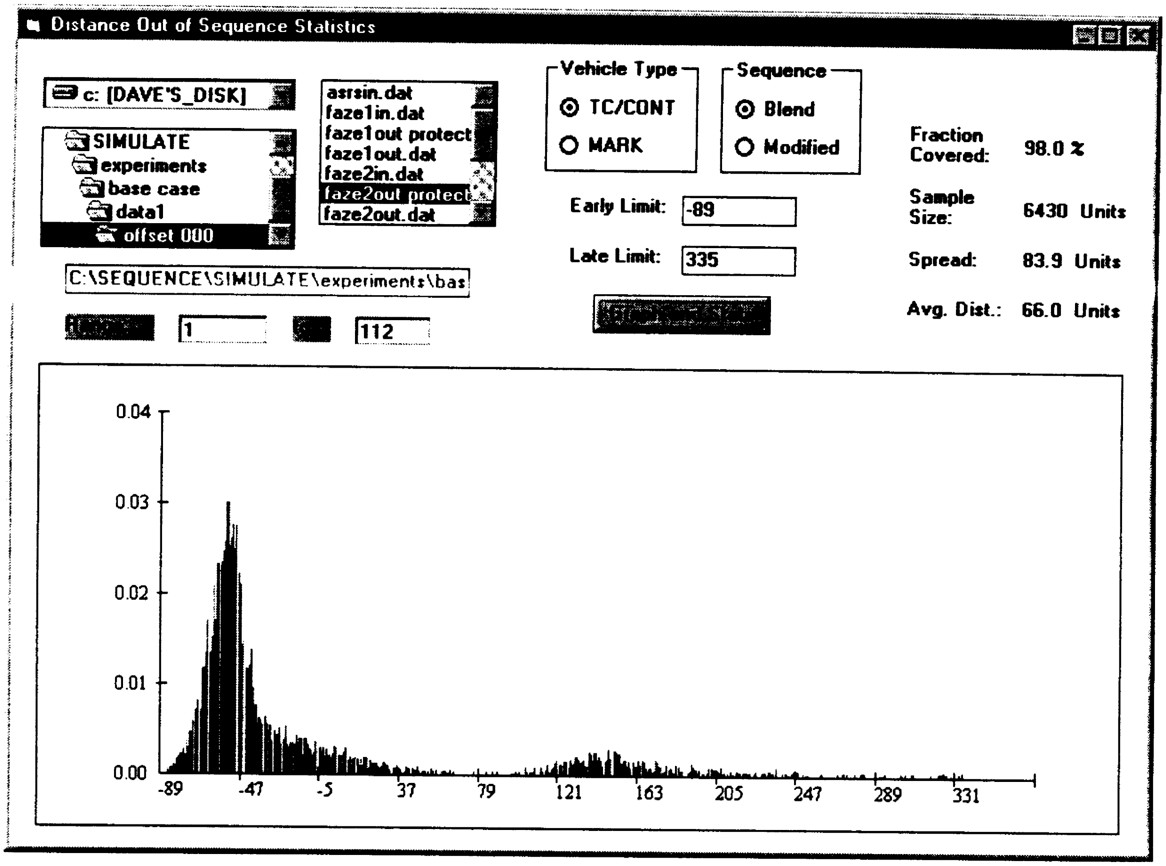
Smallest Block: 1

Average Block: 3.54

Weighted-Cost Block: 3.47

Distance out-of-sequence tool

The distance out-of-sequence tool displays a histogram of the distances that cars are out-of-sequence in the input stream.



Distance Out of Sequence Statistics

c: [DAVE'S_DISK]

SIMULATE
experiments
base case
data1
offset 000

asrsin.dat
faze1in.dat
faze1out protect
faze1out.dat
faze2in.dat
faze2out protect
faze2out.dat

C:\SEQUENCE\SIMULATE\experiments\bas

1

112

Vehicle Type
● TC/CONT
○ MARK

Sequence
● Blend
○ Modified

Early Limit: -89

Late Limit: 335

Fraction Covered: 98.0 %

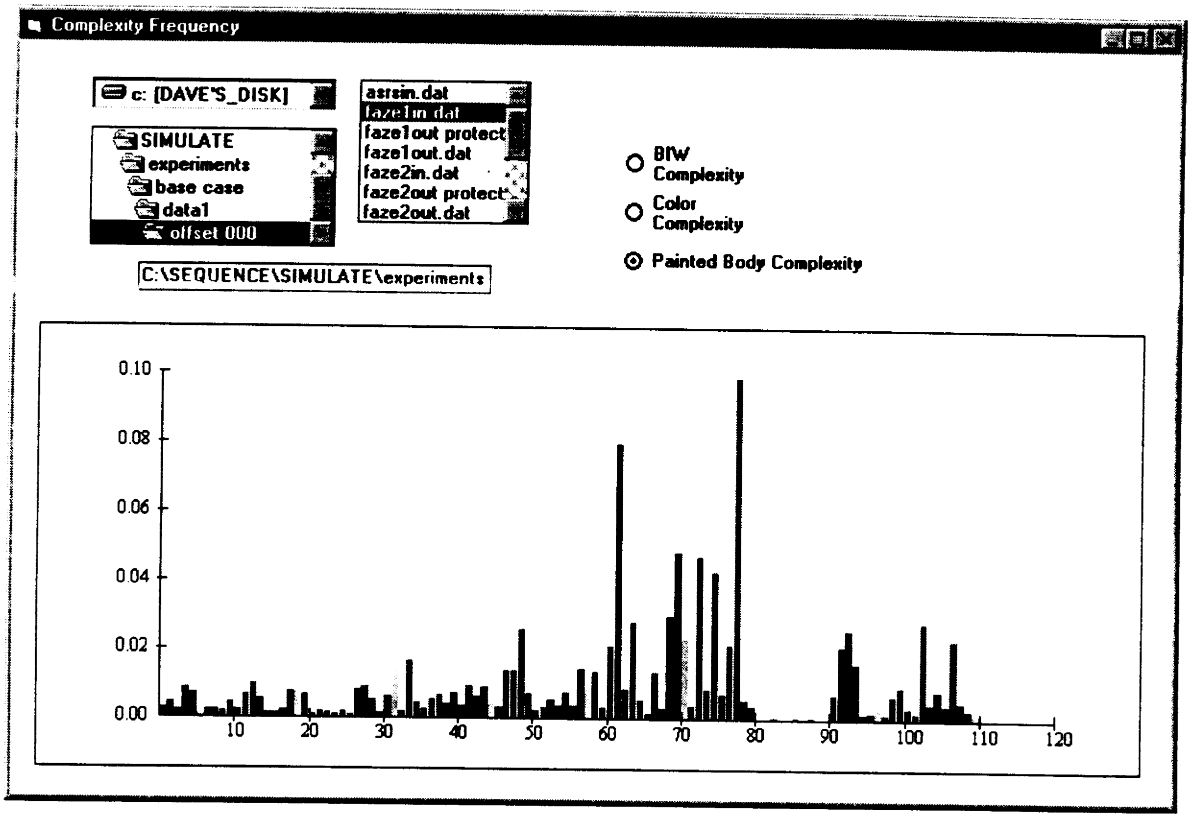
Sample Size: 6430 Units

Spread: 83.9 Units

Avg. Dist.: 66.0 Units

Complexity analysis tool

The complexity analysis tool shows the distribution of paint colors, body-in-white types, and painted-body types in the input stream.



C:\SEQUENCE\SIMULATE\experiments

○ BIW Complexity

○ Color Complexity

● Painted Body Complexity

Appendix B

SIMULATION DATA

This appendix presents the common data format used by all of the simulation components and describes the sequence data in detail. For each of the three data sets, this appendix provides a breakdown according to the following distributions: paint colors, distinct body-in-white configurations, and distinct painted-body configurations.

Common Data Format

We store the sequence data for each simulation replication in a sequential text file. Each line of the file represents a single vehicle in the sequence and contains the following fields:

1. *Modified sequence number:* if pre-sequencing is used, this field indicates the new sequence number of the vehicle. The AVS/AVI system uses this value in the body and paint shops for substitution and other sequencing decision points.

2. *Original sequence number:* the National Blend sequence number. If pre-sequencing is used, then the system reverts back to this number for sequencing decisions after the Phase-2 paint shop (e.g., in the AS/RS). If pre-sequencing is not used, the system uses this value throughout the body and paint shops.

3. *Car line:* indicates whether the vehicle is a Town Car, a Continental, or a Mark VIII.

4. *Paint color:* indicates the color of the vehicle (described below).

5. *Body-in-white type:* indicates the body-in-white configuration number of the vehicle (described below).

6. *Painted-body type:* indicates the painted-body configuration number of the vehicle (described below).

Complexity Characteristics

Color complexity description

There are 15 base-coat colors and 2 accent colors (for two-tones) in use at Wixom. Each car line can receive any one of these colors.

Body-in-white complexity description

The following factors determine the body-in-white complexity level:

Car line	(Town Car, Continental, Mark VIII)
Moon-roof	(yes, no)
Japanese export	(yes, no)

In general, not all factors apply to all car lines. In this case, the Japanese export factor applies only to the Town Car. Thus there are 8 possible body-in-white configurations. These are enumerated below:

Configuration	Car line	Moon-roof	Japanese
1	Mark VIII	No	No
2	Mark VIII	Yes	No
3	Continental	No	No
4	Continental	Yes	No
5	Town Car	No	No
6	Town Car	No	Yes
7	Town Car	Yes	No
8	Town Car	Yes	Yes

Painted-body complexity description

The painted-body complexity depends on all the same factors as the body-in-white complexity as well as the base-coat color and the accent color. These are listed below:

BIW configuration	(1, 2, … , 8)	
Paint color	(1, 2, … , 15)	
Accent color	(0, 1, 2)	{'0' indicates the absence of an accent color}

After eliminating the non-occurring configurations, 112 painted-body types remain:

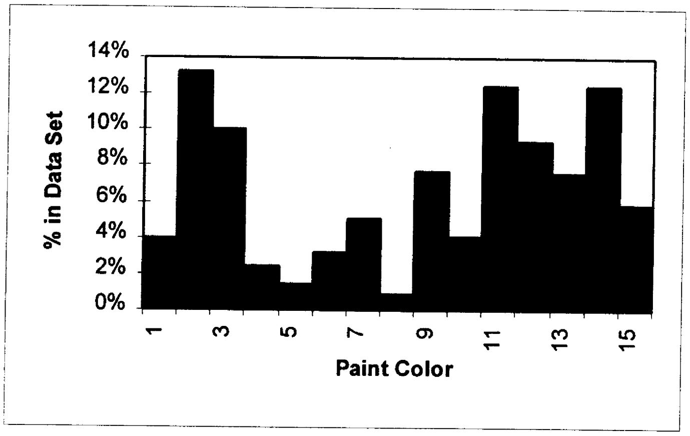
Painted-Body Configuration	Body-in-white Configuration	Paint Color	Accent Color
1	1	1	0
2	1	2	0
3	1	15	0
4	1	3	0
5	1	4	0
6	1	5	0
7	1	6	0
8	1	7	0
9	1	8	0
10	1	9	0

Painted-Body Configuration	Body-in-white Configuration	Paint Color	Accent Color
11	1	10	0
12	1	11	0
13	1	12	0
14	1	13	0
15	1	14	0
16	2	1	0
17	2	2	0
18	2	15	0
19	2	3	0
20	2	4	0
21	2	5	0
22	2	6	0
23	2	7	0
24	2	8	0
25	2	9	0
26	2	10	0
27	2	11	0
28	2	12	0
29	2	13	0
30	2	14	0
31	3	1	0
32	3	2	0
33	3	15	0
34	3	3	0
35	3	4	0
36	3	5	0
37	3	6	0
38	3	7	0
39	3	8	0
40	3	9	0
41	3	10	0
42	3	11	0
43	3	12	0
44	3	13	0
45	3	14	0
46	4	1	0
47	4	2	0
48	4	15	0
49	4	3	0
50	4	4	0
51	4	5	0
52	4	6	0
53	4	7	0
54	4	8	0
55	4	9	0
56	4	10	0
57	4	11	0
58	4	12	0
59	4	13	0
60	4	14	0

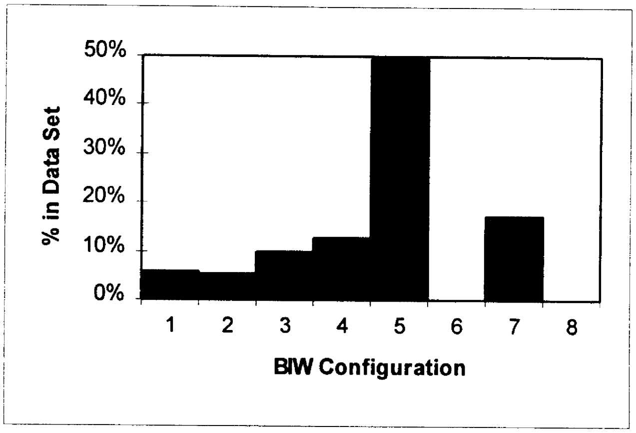
Painted-Body Configuration	Body-in-white Configuration	Paint Color	Accent Color
61	5	1	0
62	5	2	0
63	5	15	0
64	5	3	0
65	5	5	0
66	5	5	1
67	5	6	0
68	5	6	1
69	5	7	0
70	5	9	0
71	5	10	0
72	5	10	1
73	5	11	0
74	5	11	1
75	5	12	0
76	5	12	1
77	5	13	0
78	5	14	0
79	5	14	1
80	5	14	2
81	6	2	0
82	6	6	0
83	6	6	1
84	6	7	0
85	6	9	0
86	6	10	1
87	6	11	0
88	6	12	0
89	6	12	1
90	6	14	0
91	7	1	0
92	7	2	0
93	7	15	0
94	7	3	0
95	7	5	0
96	7	5	1
97	7	6	0
98	7	6	1
99	7	7	0
100	7	9	0
101	7	10	0
102	7	10	1
103	7	11	0
104	7	11	1
105	7	12	0
106	7	12	1
107	7	13	0
108	7	14	0
109	7	14	1
110	7	14	2
111	8	13	0
112	8	14	0

Data Set 1

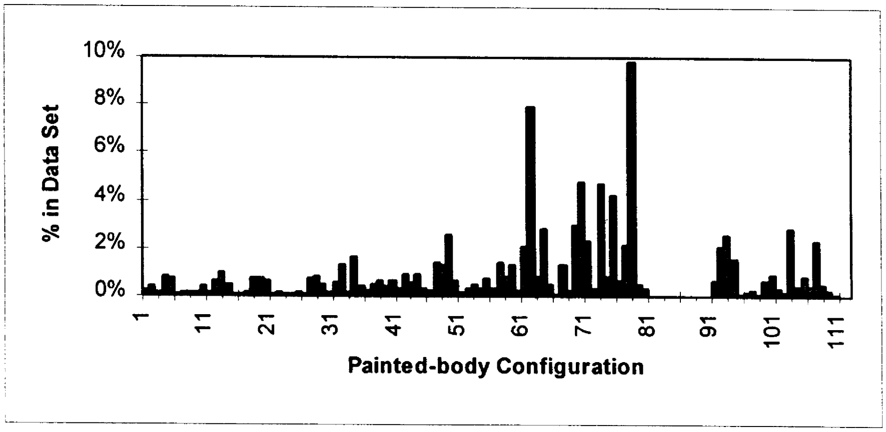
Color complexity



Body-in-white complexity

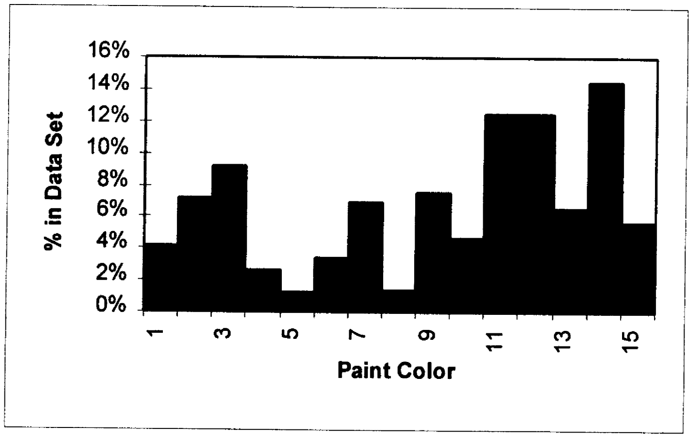


Painted-body complexity

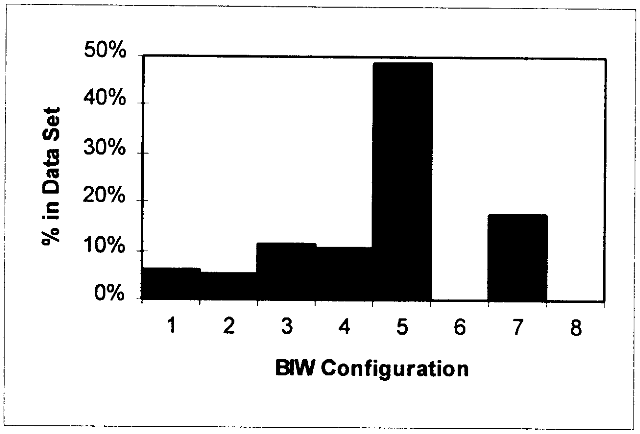


Data Set 2

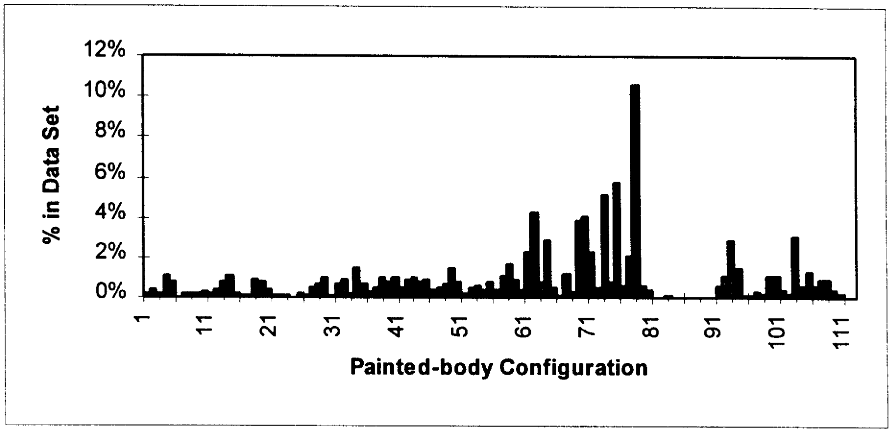
Color complexity



Body-in-white complexity

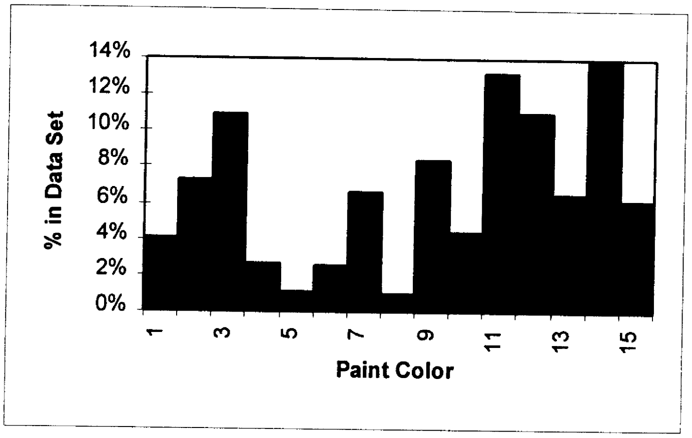


Painted-body complexity

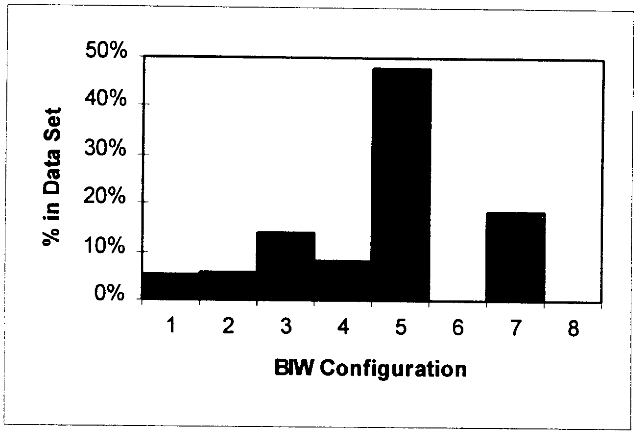


Data Set 3

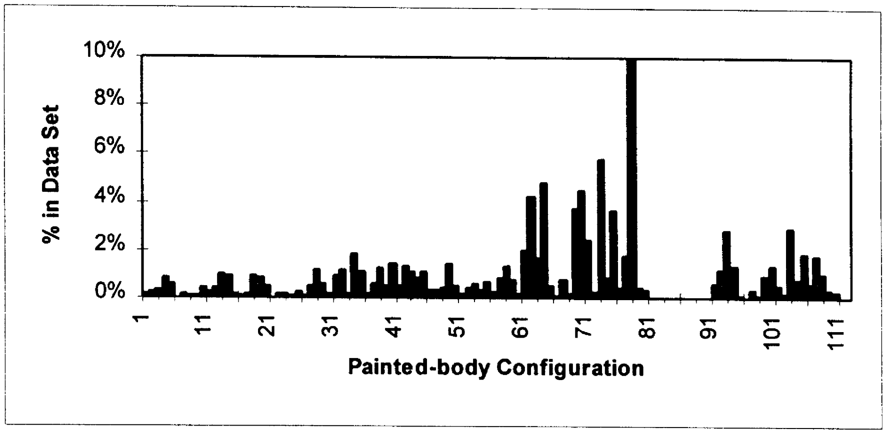
Color complexity



Body-in-white complexity



Painted-body complexity



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