Cost of Complexity:
Mitigating Transition Complexity in Mixed-Model Assembly Lines

by
Robert Addy
MEng, Naval Architecture with Ocean Engineering,
University of Strathclyde and of Glasgow, 2009

Submitted to the MIT Department of Mechanical Engineering and MIT Sloan School of Management, in partial fulfillment of the requirements for the degrees of

Master of Science in Mechanical Engineering
and
Master of Business Administration
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Abstract

The Nissan Smyrna automotive assembly plant is a mixed-model production facility which currently produces six different vehicle models. This mixed-model assembly strategy enables the production level adjustment of different vehicles to match changing market demand, but it necessitates a trained workforce who are familiar with the different parts and processes required for each vehicle.

Currently, the mixed-model production process is not batched; assembly line technicians might switch between assembling different vehicles several times every hour. When a switch or 'transition' occurs between different models, variations in the defect rate could occur as technicians must familiarize themselves with a different set of parts and processes. This thesis identifies this confusion as the consequence of 'transition' complexity, which results not only from variety but also familiarity; how quickly can a new situation be recognized, and how quickly can associates remember what to do and recover the skills needed to succeed. Recommendations follow to mitigate the impact of transition complexity on associate performance, thereby improving vehicle production quality.

Transition complexity is an important factor in determining the performance of the assembly system (with respect to defect rates) and could supplement existing models of complexity measurement in assembly systems. Several mitigation measures at the assembly plant level are recommended to limit the impact of transition complexity on system performance. These measures include improvements to the offline kitting system to reduce errors such as reconfiguring the physical layout and implementing a visual error detection system. Additionally, we recommend altering the production scheduling system to ensure low volume models are produced at more regular intervals and with consistently low sequence gaps.

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List of Acronyms

MMAL	Mixed Model Assembly Line
SMAL	Single Model Assembly Line
FMS	Flexible Manufacturing System
NNA	Nissan North America
OEM	Original Equipment Manufacturer
JIT	Just-In-Time
SUV	Sports Utility Vehicle
OCC	Operator Choice Complexity

Chapter 1 Introduction

This thesis aims to identify the quality implications of manufacturing a range of different products in a modern mixed-model automotive assembly system. This will allow for improvements in the design of such systems, and it will help the company understand the quality impact of rationalizing its product offerings. This chapter will present the problem statement and motivation to address it.

1.1 Problem Statement

As a global automotive company, Nissan Motor Co. Ltd., offers a range of automobiles to different markets and market segments globally. As is typical in the competitive automotive industry, there is a desire to leverage the firm's economies of scope by offering a vehicle in every market segment, and each segment is commonly offered a choice of propulsion technology, from traditional internal-combustion to hybrid and electric drivetrains.

To remain competitive, a modern automotive Original Equipment Manufacturers (OEM) must understand the tradeoffs that exist between different competitive dimensions. As they operate in a mature market, competing firms in the automotive industry compete on multiple dimensions, including i) cost, ii) product choice & variety, and iii) differentiation through leadership in manufacturing (i.e. quality), brand and design [1]. These dimensions are not necessarily complementary, and this study aims to identify mechanisms of interaction that exist between offering greater product choice & variety to consumers and ensuring high manufacturing quality of these products.

We can imagine that a tradeoff exists between product choice & variety and manufacturing quality. If product choice & variety is zero, we expect manufacturing quality is maximized, as only product is manufactured in a perfectly repeatable process.

Conversely, if product choice & variety is high, we expect low manufacturing quality due to the difficulties involved in manufacturing a wide variety of products. The tradeoff between these two dimensions is shown in Figure 1.1 as a convex curve, and if transition complexity can be successfully mitigated in the mixed-model process, the tradeoff curve can move to the right, where for a fixed level of product choice & variety, we can now expect a higher level of manufacturing quality.

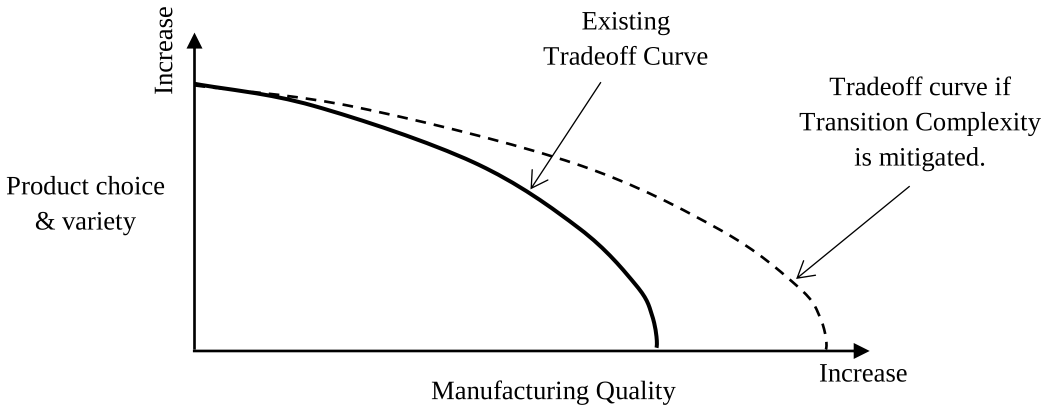

Figure 1.1 - Manufacturing Quality Tradeoff Curve

1.2 Project Motivation

The Nissan Smyrna automotive assembly plant has been configured to support the Nissan Flexible Manufacturing System (FMS) to enable the production of a wider variety of vehicles from the same plant. The Smyrna plant is a mixed-model facility which currently produces six different vehicles and the variants within those vehicle types. While this system allows the firm to adjust production levels of each vehicle to better match market demand, it poses challenges from a manufacturing perspective, where quality levels across the different vehicles may vary due to dissimilar production volumes. Maintaining high quality level in vehicles with lower production volumes is difficult as assembly line technicians will naturally have lower familiarity with products that are built less often.

Offering a high-quality product is important to maintaining customer loyalty and trust in an OEM’s brand, and it has been identified as the most important factor influencing a consumer’s purchasing decision [2] . Nissan has been consistently ranked by JD Power as having above average quality among automotive brands in the US Initial Quality Study [3] and the firm maintains high product quality objectives within the corporate objective of ‘operational excellence’ contained within the “Nissan M.O.V.E. to 2022” corporate plan (Nissan 2017).

1.3 Project Objective

Since the consumer market demands a product variety and given that there are clear reasons for a single assembly facility to be able to build such a variety of model to adjust for demand, we are seeking a preferential policy for sequencing production that provides the variety the market needs while accounting for switching costs between one model and the next.

Currently, the mixed-model production process is not batched; assembly line workers might switch between assembling different vehicles several times every hour. We can think of the mixed-model production process as having a batch size of one; there could be a switch to a different model after every vehicle. When a switch (or ‘transition’) between different models occurs, variations in the defect rate occur as workers must familiarize themselves with a different set of parts and processes required for the next model on the assembly line.

Observation of the defect data has revealed increased defect rates after transitioning between certain models, which we propose is a direct result of the transition complexity in the mixed-model assembly system. The objective of this study is to define and quantify this ‘transition’ complexity and recommend measures to mitigate the impact of ‘transition’ complexity on vehicle production quality.

Chapter 2 Background

2.1 Nissan Smyrna Assembly Plant

Nissan North America (NNA) is a subsidiary of Nissan Motor Ltd (NML), the publicly traded Japanese auto maker, headquartered in Yokohama. Nissan North America (NNA) manufactures and distributes a wide range of vehicle types (including cars, SUVs, trucks and light commercial vehicles) under the Nissan and Infiniti brands. NNA operates three non-unionized manufacturing and assembly facilities: vehicle stamping and assembly plants in Smyrna, Tennessee and Canton, Mississippi, and a powertrain plant in Decherd, Tennessee.

Established in 1983, the Nissan Smyrna assembly plant is the highest-volume automotive assembly plant in North America, with the capacity to produce 640,000 vehicles annually [5]. The plant represents a $7.1 billion investment for Nissan, and it has been continually upgraded with the latest technology since its initial construction. The Smyrna plant currently produces the Nissan Altima, Nissan Rogue, Nissan Pathfinder, Nissan Maxima, Nissan Leaf and Infiniti QX60.

The plant is divided into 3 main areas; Body & Stamping, Paint and Trim & Chassis. The Body & Stamping and Paint areas of the plant are highly automated and very few parts of the vehicles are installed in these areas. This study will focus on quality outcomes in the Trim & Chassis area of the assembly plant. This area of the plant assembles the vast majority of the parts in each vehicle and almost all of the assembly work is performed manually by skilled technicians at stations on the assembly line, hence human factors are an important consideration in this area of the plant.

2.2 General Plant Configuration

The Nissan Smyrna plant currently assembles six models, with three models dedicated to each of two assembly lines in the Trim & Chassis area.. It is not possible to switch between lines, each group of three models is dedicated to a single line, generally for a whole year. This partitioning of models to specific lines is due to the specialized equipment required to assemble different types of vehicle and differences in assembly sequence.

For example, if sales of Model A, B & C turn out to be very low, but sales of Models D, E & F are very high, the plant cannot easily change to having both assembly lines build Model D, E & F, such a change might require several weeks of upgrade and modification work. SUV's are physically larger than sedans, so an assembly line configured for SUV's would have equipment that can handle the larger and heavier components such as doors, sunroof panels and engines, whereas a sedan assembly line may not be configured to deal with these components.

Each assembly line has several segments (which can be thought of as stations), and each segment has a specific 'kit-cart' of parts delivered to the assembly line by an autonomous guided vehicle (AGV) for the line technicians to install. The vehicles move continuously through the line segments at a fixed-speed on a large conveyor, and new kit-carts are brought to the assembly line at the beginning of each segment. The kit-carts move at the same speed as the vehicles on the conveyor, allowing the line technicians to move easily back and forth between the vehicle and the kit-cart.

Each 'kit-cart' is specific to a single vehicle, and they are delivered in a sequence corresponding to the sequence of vehicles on the assembly line. The 'kit-cart' of parts is manually pre-assembled in a dedicated 'kitting area' which is an in-plant part storage area. These areas utilize pick-to-light systems and instructional displays to ensure the correct parts are chosen.

The 'kitting area' for each line segment will hold most of the parts required to assemble the three different models (and variants) on that line segment. The 'kitting area' could store many thousands of parts and only a few tens or hundreds are chosen for the assembly tasks on a line segment. The line technician will install all parts in the ‘kit-cart’ into the vehicle, which eliminates the selection aspect of the ‘choice complexity’ on the assembly line.

Refer to Figure 2.1 for a diagram of the typical assembly line configuration, showing two-line segments A & B;

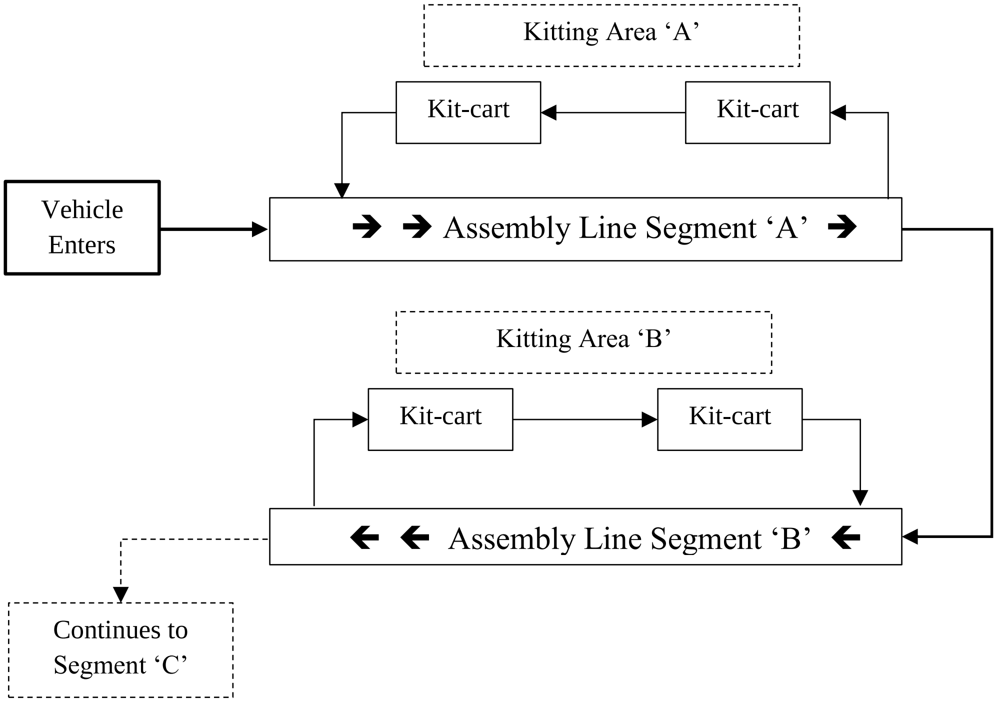

Figure 2.1 - Typical Assembly Line Configuration

The ‘kit-cart’ travels along the assembly line with the vehicle being assembled, they are removed at the end of a line segment, sent back through the relevant ‘kitting area’ to be re-stocked with specific parts for the next vehicle in the sequence, and then sent back to the start of the assemble line segment, in a continuous loop.

In this assembly line configuration, line technicians are assigned to a specific line segment or ‘zone’, which enables specialization on a group of related tasks, such as powertrain installation, or interior trim fitting.

2.3 Mixed-Model Production

Nissan North America (NNA) has configured the Smyrna, TN, and Canton, MS, plants to operate with a mixed-model assembly process, which enables flexibility in production volumes, as the build volume of different vehicles can flex up or down to better match demand throughout the year. This operating strategy also enables Nissan to be produce a greater range of vehicles at each plant, thus allowing the company to offer more vehicles while controlling capital expenditure on fixed assets.

This is a useful production system for low-volume but high-variety products, provided there is adequate similarity between the products, as the switch-over cost between models should be small. Mixed-model production ensures a more continuous flow of each model, and it generally reduces the in-process and finished goods inventory [6]. A mixed-model production system is one of the foundations for applying a Just-In-Time (JIT) supply chain system, as it provides smoother production, compared to batch processing.

2.4 Overview of Current Mixed-Model Sequencing Methodology

The assembly line system at Nissan Smyrna allows for multiple models to be built on a single assembly line, with an effective batch size of one vehicle. Depending on demand for each type of vehicle, assembly line technicians could find themselves assembling five sedans in a row, or they may switch from a sedan to a compact and then to a sports utility vehicle (SUV).

The dominant consideration which affects mixed-model scheduling is ‘capacity balancing’, where the production schedule of different vehicles is created based on the varying cycle time for the build process of each vehicle. For example, a more complex (higher or premium trim level) vehicle may take slightly longer than average to assemble due to the increased feature content, so the scheduling system ensures that this vehicle is not built in batches and is instead mixed with other vehicles that take slightly less time than average to assemble.

This capacity balancing allows line technicians to fall behind when assembling more complex vehicles and then ‘catch up’ when assembling simpler vehicles. As the assembly line is split into multiple sections, ‘capacity balancing’ is important to ensure that technicians can complete the tasks required within their line segment or ‘zone’, otherwise they may have to stop the line to complete the work, as they cannot move with the vehicle into the next zone.

A greater volume of low and middle trim level vehicles are typically sold than higher (premium) trim levels, due to the reduced price of lower and middle trim level vehicles capturing a larger market of potential consumers. Consequently, premium trim vehicles with a batch size of one are mixed into larger batches of middle and low trim level vehicles. Therefore, the higher (premium) trim level vehicles having a higher probability of increased transition complexity.

2.4.1 Choice Making and the Hick-Hyman Law

Each vehicle model and trim level have a variable part content, depending on the feature content of the vehicle, for example, premium trim levels could have additional parts for an enhanced entertainment system, or additional electrical wiring for heated seats. At the start of each assembly line segment, a kit-cart which is specific to each vehicle, arrives at side of the assembly line. Even though the kit-cart has been compiled in an offline part storage area, the line technicians must make a series of correct choices; i) select the correct parts, ii) in the correct order, and iii) select the correct tools (or fixtures) to complete the work in their segment. Each of these choices requires time to be made correctly.

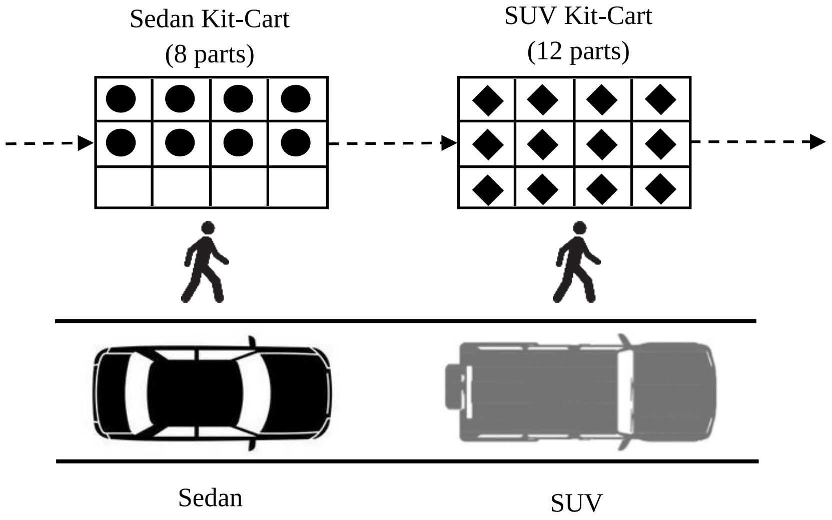

Figure 2.2 - Example Choice Making Process

To visualize the choice making process on the assembly line, we refer to Figure 2.2 above. The sedan kit-cart has 8 parts to be installed, each part represented by the black circles, and half of these parts requires a different tool choice for installation. Thus, the sedan requires twelve choices; eight part choices plus four tool choices. The SUV kit-cart has twelve parts, each part represented by the black diamond in the kit-cart, and all of those parts require a different tool choice for installation. The SUV requires twenty-four choices, twelve part choices plus twelve tool choices. In this example, the SUV requires double the choices of the sedan, and hence the cycle time for the SUV will be longer on this line segment.

In reality, at the Smyrna plant, each kit-cart could hold tens of parts, and each part may require the correct fixtures to be chosen (i.e. multiple screws or bolts) in addition to the correct tool choice (i.e. torque wrench). Therefore, each assembly line segment will require hundreds of correct choices to be made.

If a greater number of parts than average arrives in a kit-cart, we would expect the line technician to take longer to assemble these parts, as there are simply more parts to install, and each choice requires time to be made.

The variation of cycle time, which is proportional to the vehicle part content, is a consequence of human choice-making activities which obeys the Hick-Hyman Law [7]. The Hick-Hyman law states that average choice reaction time (RT) is linearly proportional to the logarithm of the number of alternatives, if all alternatives are equal. The Hick-Hyman law is generalized as follows;

$$Mean\ Choice\ RT = a + bH \tag{2-1}$$

Marin et al. define Choice complexity as the average uncertainty or randomness in a choice process, which can be described by a function H (representing information entropy) in the following form [7];

$$H(X) = H(p_1, p_2, \dots, p_m) = -C \sum_{m=1}^{M} p_m \log p_m \tag{2-2}$$

Where p_m is the probability of a choice taking the m^{th} outcome. Here H is exactly equal to $[\log_2 n]$, where n is the number of alternatives (i.e. choices). This arises as all of the p_m*'s* are equal, since the choice process is independent and identically distributed (iid) and all alternatives are equally likely to occur. The variables *a* and *b* are constants which must be determined empirically by fitting a line to measured data. These variables will account for characteristics of the choice process, such as difficulty or lack of familiarity.

While the cycle time (i.e. assembly time) of vehicles assembled in the Trim & Chassis section of the Smyrna plant is based on actual assembly experience, it is nevertheless a useful result that cycle time obeys the Hick-Hyman law. This is due to the vast majority of the processes in the Trim & Chassis area being manual (i.e. human) choice processes. We therefore know that a reduction in the number of choices at each station will result in a lower cycle time.

In additional to the variable part content mentioned above, each vehicle model may have a different build sequence, so the type of parts delivered to the assembly line in the kit-cart will be different for each vehicle, which increases the difficulty of the choice making process. Equally, when assembling low-volume models the line technician is less familiar with the parts and tools required to install them, further increasing the time taken. Variables a and b can describe the choice making difficulty of the process.

2.4.2 Variation of Cycle Time

The variation of cycle time with vehicle is shown in Figure 2.3 below. The part content (i.e. the assembly jobs required) for each vehicle drives the cycle time requirement, i.e. vehicle with more parts have a higher cycle time. Therefore, we would expect vehicles with a higher cycle time to have a higher defect rate due to higher entropy and the increased stress placed upon line technicians of having assemble a more complex vehicle in an allotted time.

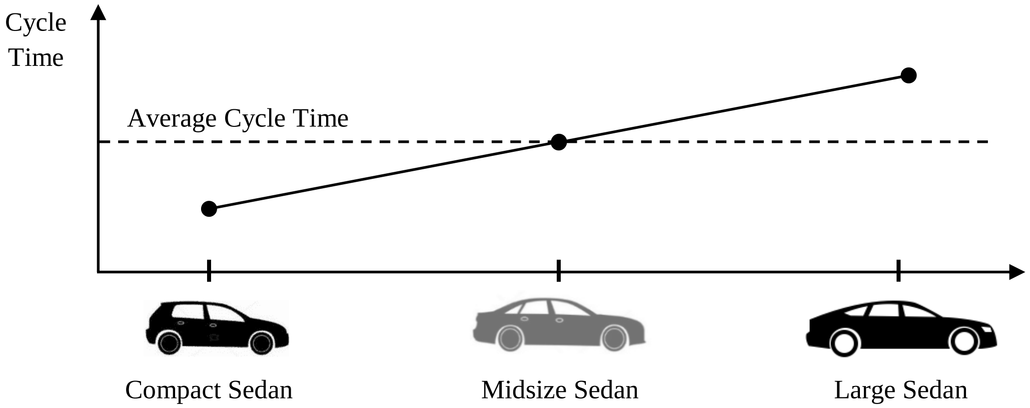

Figure 2.3 - Diagram of Vehicle Cycle Time in a Three Model Assembly System

If these three vehicles are built on the same line, the expected build quantity will have to be matched with the cycle time. The assembly line will be well balanced in terms of cycle time if the build quantity of the compact and large sedan are equal, and therefore will cancel each other out. If the midsize sedan is the dominant model, then the assembly line can tolerate un-balanced production of the compact sedan and large premium sedan and the overall average cycle time will be close to the average. In this example, variation in cycle time

For a mixed-model assembly line with only two vehicles as shown in Figure 2.4 below, the average cycle time would be balanced considering the production volume of the two vehicles. In the below figure, if the midsize sedan is 75% of the production volume, and the large premium sedan is 25%, then the average cycle time on the assembly line will be 25% greater than that of the midsize sedan, i.e. the cycle time changes in proportion to the difference in production volume.

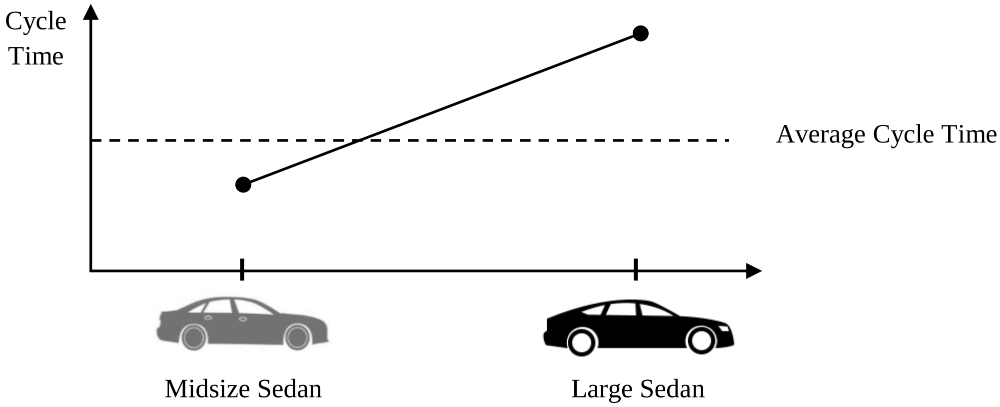

Figure 2.4 - Diagram of Cycle Time in Two Model Assembly System

2.5 Mixed-Model Sequencing Constraints

The current mixed-model sequencing constraints relate to capacity balancing, as described above. The sequencing system is constrained by how frequently a vehicle with a longer than average cycle time can be produced on the assembly line. For example, if a vehicle has a sunroof, there are some additional processes which must be carried out, compared to a vehicle without a sunroof. These additional processes could include lifting a glass panel above the vehicle into place, connecting additional electrical components to control the sunroof and function testing all of these additional components. As this vehicle with a sunroof has a longer cycle time, the vehicle before or after it on the assembly line must take less than the average cycle time in order for the line workers to ‘catch up’ the time and maintain the target production level. Similar constraints apply to a variety of other vehicle options, as well as entire vehicle models.

A high-end vehicle model may have relatively low forecasted production volume, where on average, it is produced at a rate of 1-in-10 vehicles. It may additionally be subject to a scheduling constraint where it cannot be assembled at a rate greater than 1-in-5 vehicles due to the higher than average cycle time to assemble this vehicle While on average this constraint appears to be non-limiting, if the plant intends to increase the production rate of the vehicle, it can only increase up this scheduling constraint to maintain capacity balance.

The constraints currently defined in the scheduling system define the maximum frequency with which a model can be produced, but there are no minimum constraints used, for example, there are no constraints requiring a minimum production rate of 1-in-20.

2.5.1 Definition of Sequence Gap

In the mixed-model assembly process, the ‘gap’ between two models of the same vehicle is variable. The gap preceding each vehicle was used to examine the relationship between the sequence gap of an individual vehicle and build quality. Figure 2.5 below illustrates a sequence gap of 2 for Compact vehicle #4, corresponding to a assembly rate of 1-in-3. Figure 2.6 illustrates a sequence gap of 4 for Compact vehicle #6, corresponding to an assembly rate of 1-in-5. In Figure 2.5, the #5 sedan has a sequence gap of 1 as it was preceded by a compact model, and #6 sedan has a sequence gap of 0, as it was preceded by another sedan.

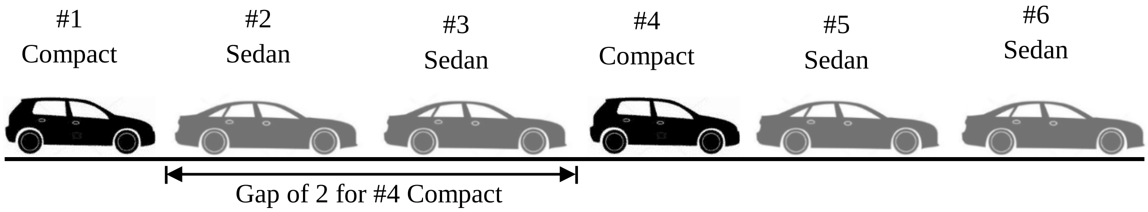

Figure 2.5 - Diagram of Sequence Gap of 2, or 1-in-3 Assembly Rate

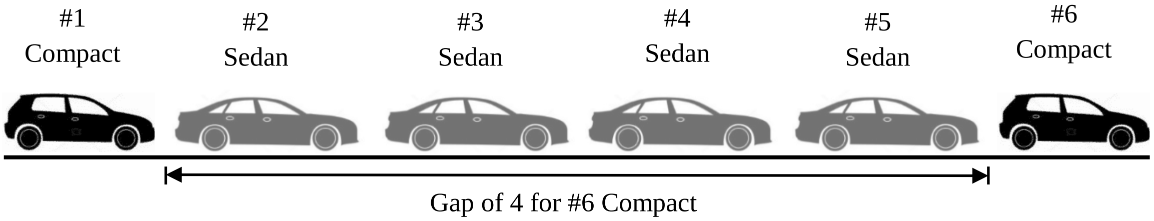

Figure 2.6 - Diagram of Sequence Gap of 4, or 1-in-5 Assembly Rate

2.6 Overview of Vehicle Models and Variants

A modern automotive OEM could offer hundreds of different vehicles to consumers. For example, each model could be offered with 2 drivetrain options; front-wheel drive and all-wheel drive. Each of these drivetrains could be offered with solid roof or sunroof, and all of these options can be offered in perhaps 5 trim different trim levels, with multiple variants within each trim level containing different feature packages and varying interior finishes. This thesis will not examine models down to this detail, as it is often too granular to produce meaningful results due to ever decreasing sample sizes as we get more specific. This study will concentrate on comparing defect data at the model level and trim level within each model.

2.6.1 General Nomenclature

Within this thesis, the models assembled at the Smyrna plant shall be denoted as Model A-C and Models D-F, where each group of models is assembled on a separate assembly line. The various trim levels within each model denoted as 1-5. Where the term Model A is used, it includes all the trim levels within the model. If a specific trim level is referred to, it will be denoted as, for example A-1, which denotes Model A, trim 1.

Chapter 3 Initial Observations from Defect Data

This chapter outlines several initial observations from the defect data. Initial analysis of the data is undertaken to understand the general systematic behavior of the assembly system and determine if the assembly plant staff's observations of the system's behavior are substantiated.

The defect rates of Models A-C are compared to Models D-F, where these two groups of vehicles are produced on different lines and with differing production volumes. Within the grouping of Model A, B & C on one assembly line, it is known that Models A & B share a large number of common parts and assembly processes, while Model C has significantly different parts and processes compared to Model A & B.

Within the grouping of Model D, E & F, Models E & F share a large number of common parts and processes, while Model D differs in terms of parts, it shares common processes with Models E & F.

3.1 Overview of Data Sources

This study utilizes data generated from the in-plant defect logging system at the Smyrna assembly plant along with manufacturing information for each vehicle. Here the term 'defect' is used generally to describe any unsatisfactory condition logged in the system during assembly, which will then be rectified prior to completion.

3.1.1 Defining Relevant Defect Data

For the purposes of this study, defect data includes all issues logged in the system within the 'Trim & Chassis' area of the plant. This data is logged immediately after a defect is detected at the side of the assembly line in dedicated computer terminals. Defects detected and rectified in the Body & Stamping and Paint sections of the plant are not considered part of this study, as our point of interest is how part complexity affects defect rates. Defect data for vehicles which are already in-service (i.e. from customers or end-users) is not considered in this study, such data would include part defects originating with suppliers and defects resulting from a variety of external factors which are difficult to differentiate.

3.1.2 Design Data – Bill of Materials, numbers of parts being assembled

For vehicles assembled at the Smyrna plant (i.e. specific model, trim & variant), the bill of materials was extracted, which provided a complete list of the parts (and sub-assemblies) which are assembled at the plant. For example, a headlamp sub-assembly might consist of many individual parts, but this would be considered a single item in the Smyrna plant, equivalent to a part. The vehicle models produced at Smyrna are offered in a variety of trim levels, each targeted at a different market segment. Each of these trim levels is then offered in multiple variants, each with a variable part content.

3.1.3 Defect (Quality) Data from In-plant Systems.

Defect data from the Trim & Chassis part of the assembly plant was extracted from the in-plant defect logging system for a 12-month the period in 2018-19. The defects were logged during in-plant assembly processes and rectified during or after assembly. The defects logged could be missing parts, parts not installed according to specifications, or even dirty parts which must be cleaned.

The defects recorded for each vehicle are normalized by dividing by the number of parts within the vehicle and dividing by 1,000, so that a defect rate per 1000 parts is used for comparison across vehicles. We can expect a vehicle with more parts to have a greater defect rate, as there are more installation operations to perform, each of which can be correct or incorrect. Defect rates in this study are normalized with respect the dominant vehicle on the assembly line, i.e. the vehicle with the greatest production volume will have a defect rate of 1.0.

3.1.4 Scheduling Data for Build Sequence

The actual build sequence of vehicles in Trim & Chassis part of the plant was used. The actual build sequence of vehicles in each section of the plant varies, due to the designed buffer areas where finished products from one part of the plant are held for quality inspection before being released to the next section, thus the sequence in which vehicles are assembled in Body & Stamping is different from the sequence in the Trim & Chassis section.

3.1.5 Data Selection for Analysis

During the 12-month period for which data was extracted, there are many minor and major model launches, where a particular model may have styling updates (minor launch), or a whole new vehicle may be launched (major launch). After each minor or major model launch, there will be a learning curve where the assembly line technicians must become familiar with the updated parts and assembly sequence for the vehicle.

The dramatic learning curve associated with a new model launch can be seen in Figure 1 above; the defect rates reaches a steady state after approx. 4 months of production. The objective of this study was to examine the effect of steady-state processes on defect rates, so two periods of approximately 6-8 weeks were selected for analysis, where the defect rate was relatively constant for all vehicles, and no observable learning curve existed.

3.1.6 Combining the Data

In the current mixed-model production system, defect rates for each vehicle are tracked to enable root-cause analysis of defects identified during the assembly process. This defect tracking is performed for each vehicle in isolation, and the effect of build sequence is not accounted for when examining defect rates. The different vehicles built on the same assembly line are assumed to be sufficiently similar such that the switching cost of transitioning between different vehicles is zero. This assumption is one of the core assumptions of the mixed-model sequencing system [6]

To quantify this switching cost between models, the defect data has been examined from the point of view of sequence, i.e. what influence, if any, does one vehicle have on the following vehicle.

3.1.7 Vehicles for non-US markets

The Smyrna plant produces vehicles designed for a range of markets outside the US domestic market, many of which have specific parts required by local market regulations.

The different part content of these vehicles means that the build sequence is often modified to balance the jobs over the assembly process. Additionally, the line technicians are not familiar with many of these specific parts, due to the low production volumes of the export vehicles leading to potentially higher defect rates for a vehicle model. As this increase in defect rate is attributable to specific parts in export model, rather than the normal plant processes, these export vehicles are excluded from the data set.

3.2 Learning Curve in Assembly

The full 12-month defect data for a high-volume vehicle Model A which was a major model introduction during the period analyzed is shown below. After the start of production (SOP), the defect rate declines rapidly and remains largely flat, even with fluctuations in monthly production volume. This indicates that there is a significant learning effect, where the plant workforce needs to assemble a certain number of units in order to reach maximum level of familiarity (and competency) with the vehicle model.

For this high-volume vehicle, Model A, we plot defect rates for each of the five trim levels and find a strong relationship between the trim levels, despite high variability in the production volume. This indicates a combined learning effect which is independent of the production volume for each trim level and is dictated by the combined production volume for all variants. This can be explained by the fact that most parts across the variants are similar, and even where parts may differ, the general assembly processes do not.

Vehicles with lower production volumes do not reach this flat level of defect rates, as they are not being assembled frequently enough for the workforce to reach this maximum level of familiarity (and competency) with the vehicle's parts & processes. We observe that the defect rate is negatively correlated to monthly production volume, which can be thought of as the familiarity level of the workforce reducing gradually over time. Figure 3.1 below shows charts of monthly build volume plotted with the trend of average defect rate for Model A & B (Model C is not shown but displays a trend similar to Model B).

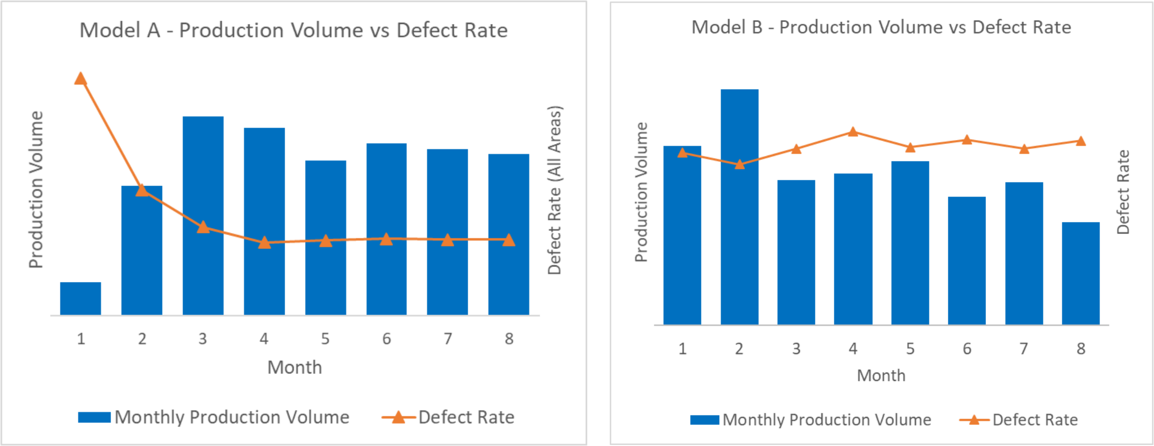

Figure 3.1 - Learning Curve for Model A & B

Due to the learning curve observed for Model A, data for months 1-3 will not be considered as part of this study, as they are not the result of a steady-state system.

3.3 Defect Rates on Each Assembly Line

For a steady state production period, we can compare production volume, defect rate and sequence gap for Model A-C.

Table 3.1 - Model A-C Comparison of Production Volume & Defect Rate

Vehicle Model	Production Volume	Normalized Overall Defect Rate	Average Sequence Gap Between Models
Model A	75%	1.00	0.3
Model B	20%	1.40	4.2
Model C	5%	2.82	19.7

Referring to Table 3.1, we can see that the production volumes for Model B & C are low, and thus the elevated defect rates could be the result of reduced familiarity among workforce with these models. Model A & B share many common parts and assembly processes, while Model C differs greatly in parts & assembly compared to Model A & B. The sequence data for Model A-C does not display a regular repeating production pattern.

The production volume, defect rate and sequence gap for Model D-F are given in Table 3.2 below. There is less variation in the defect rates between the three models, and difference in the production volume is also reduced. In this case, Model E & F share a large number of common parts and similar assembly processes, and they share only a small number of parts with Model D. The sequence data for Model D-F shows that in general, this assembly line follows a dominant repeating pattern of D-E-D-F.

Table 3.2 - Model D-F Comparison of Production Volume & Defect Rate

Vehicle Model	Production Volume	Normalized Overall Defect Rate	Average Sequence Gap Between Models
Model D	51%	1.00	1.0
Model E	26%	1.11	2.8
Model F	23%	1.20	3.5

When we compare the defect rates of Model A-C and Model D-F, factors such as the vehicle characteristics and how the commonality of assembly processes with the dominant model on the assembly line are important.

Model E & F share a common product architecture and have a large proportion of common parts and therefore this group of three vehicles can be approximated as one assembly line switching between two models, which indicates why the normalized defect rates are relatively close. The variance in the defect rate can be reasonably explained by Models E & F having a higher part content and cycle time than Model D. That is, the line technicians assembling Models E & F will have to install more parts in the same amount of time, and therefore we might expect higher rates of defects due to two factors; i) greater number of choices, and ii) greater stress to complete the job in the allotted time.

Model A & B share a common platform and many common parts, yet the normalized defect rate of 1.40 is greater than that of Model E & F, despite similar production volumes. The lack of repeating production pattern for Model A-C could explain the greater variance in defect rates from the dominant model. The product architecture of Model C is significantly different from Model A & B, coupled with low production volume of 5% could elucidate the high normalized defect rate of 2.82.

3.4 Effect of Sequence Gap

The apparent relationship between production volume and defect rate indicates that we might expect the defect rate of an individual low-volume vehicle to be correlated with the sequence gap between low-volume vehicles. That's is, if a low-volume vehicle is built with a frequency of 1-in-10, we would expect higher defect rates than if it was built with a frequency of 1-in-5. This leads us to expect that the sequence 'gap' is an important factor in determining vehicle quality in the mixed-model production process, where the 'gap' is defined as the number of different vehicles between two vehicles of the same model.

Increasing the 'gap' between two models of the same type, the line workers become less familiar with the operations and parts required for this vehicle and therefore the defect rate could rise. In the case of Model A, we expect that this model is built so frequently that the defect rate has reduced to the lowest steady-state rate, as worker familiarity with this model has reached a maximum level.

Generally, Model A has a gap less than or equal to 1 as it is the dominant model, while Model B & C have gaps ranging from 1 to over 50, as they are slotted into the production process. Only US domestic models have been analyzed, the export models have been excluded from this analysis, as they have a significant number of different parts which will affect the defect rates since assembly workers are less familiar with these parts.

3.4.1 Analysis of Sequence Gap

Plots of the average defect rate against the sequence gap for Model B & C are shown in Figure 3.2 below and shows no strong relationship between these two factors at the individual vehicle level. For Model B, 95% of the vehicles had a sequence gap between 1 and 9. The data plot was truncated at sequence gap of 15, due to there being a small number of data points at higher values of sequence gap. For Model C, 69% of the vehicles had a sequence gap between 1 and 20. The data plot was truncated at sequence gap of 20, due to the low number of data points above this value. No reliable relationship between sequence gap and defects rate was found.

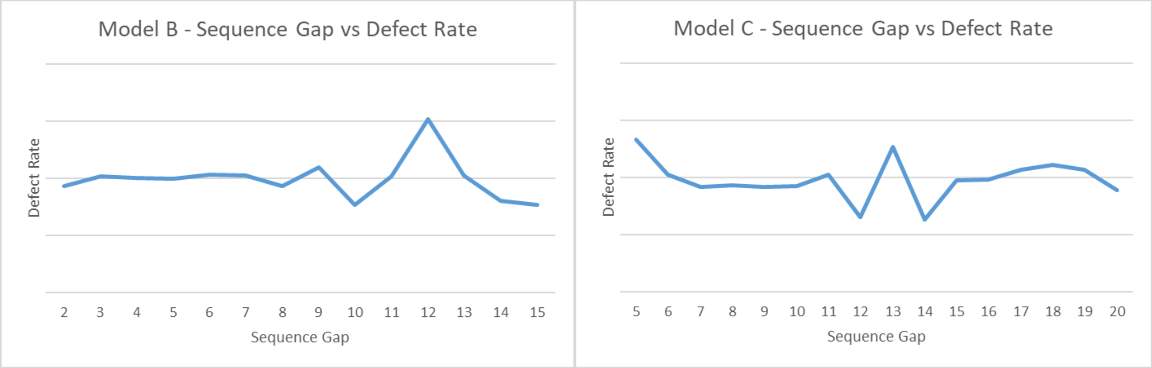

Figure 3.2 - Sequence Gap vs Defect Rate for Model B & C

The plots in Figure 3.2 above show that the vehicle-specific sequence gap is not an important factor in determining the defect rate in the mixed-model process. Although there is a link between the monthly production volume and the defect rate (as shown in Figure 3.1), the rate at which workers gain or lose familiarity with any particular vehicle model appears to be slow; lower build volumes for a period of weeks or months will contribute to greater defect rates, but these are gradual declines over time. Therefore, production volume fluctuation produces defect rate variation at the monthly level, but not at the daily (or hourly) level.

3.5 Effect of Preceding Vehicle on Defect Rates

The sequence gap does not appear to an important factor in determining defect rates of individual vehicles, and therefore the switch between different vehicle models is investigated to establish its contribution to defect rates. Both Model B & C are almost always preceded by Model A due to the production volume mix of the period analyzed, and we expect that this switch or ‘transition’ between different models contributes to the defect rates of Models B & C being greater than Model A.

Two-thirds of the Model A vehicles are preceded by other Model A vehicles and so the average complexity of the switch (or ‘transition) for Model A is lower, which contributes to the reduced defect rates for Model A vehicles, along with the greater degree of workforce familiarity with this vehicle.

Table 3.3 - Effect of Preceding Vehicle on Model A Defect Rate

Dominant Model	Preceding Vehicle on Assembly Line	Normalized Defect Rate
Model A	Model A	1.00
	Model B	1.03
	Model C	1.13

The results in Table 3.3 above show that the preceding vehicle on the assembly line has an effect on defect rate. If a Model A vehicle is preceded by another Model A vehicle, the normalized defect rate is 1.00, but if a Model A vehicle is preceded by a Model C vehicle, the normalized defect rate is 1.13 (i.e. a 13% higher defect rate). In this case that Model A & B share a greater number of common parts than Model C does with either A or B. Since Model B & C are always preceded by a Model A vehicle, due to the production volume mix, this comparison for those vehicles is not possible. This data only includes US domestic vehicles, and vehicles preceded by other US domestic vehicles.

Table 3.4 - Comparison of Designed Cycle Time

Vehicle Model	Designed Cycle Time
Model A	Average
Model B	Above Average
Model C	Below Average

Table 3.4 above compares the designed cycle time for each vehicle, which is a summation of the time to perform each individual assembly task for each vehicle. This method of calculation essentially follows the Hick-Hyman Law, as cycle time is proportional to the number of parts,

The increase in Model A defect rate following a Model C vehicle occurs despite Model C having a lower cycle time than Model A, and we would therefore expect that the line technicians would have excess time to assemble the Model A vehicle. It appears from this data that this is not the case, and actually the Model C vehicle takes longer to assemble than predicted, thereby reducing the time available for assembly of the Model A vehicle and causing a higher defect rate in those vehicles. The variation in defect rate is shown visually in Figure 3.3 below.

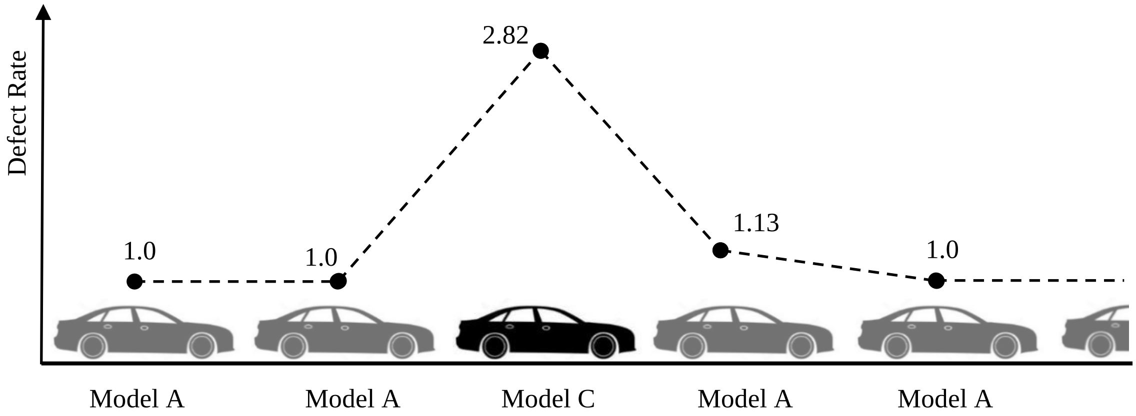

Figure 3.3 - *visualization of defect rate variation across Model A-C sequence*

For Model D-F the transition between models has a minor effect on defect rates, which could be a consequence of the regular repeating production sequence on this line, and because of the greater extent of part and process sharing across these three models. This combination of factors will reduce the transition complexity. In Table 3.5 below, Model D preceding another Model D vehicle appears to elevate the defect rate, however this is due to this transition occurring only where low-volume premium trim levels of Model D are produced, and therefore we have a higher part content combined with line technicians being less familiar with the additional part content of these vehicles. This data is also collected from 6-8 weeks of production data, not over a whole year, and therefore the effect of these transitions on defect rates at other points during the year could vary.

Table 3.5 - Effect of Preceding Vehicle on Model D Defect Rate

Dominant Model	Preceding Vehicle on Assembly Line	Percentage of Transition	Normalized Defect Rate
Model D	Model D	14%	1.04
	Model E	46%	1.02
	Model F	40%	1.00

3.6 Effect of Number of Parts on Defect Rates

Referring back to the Hick-Hyman Law (Section 2.4.1), we would expect vehicles with a lower number of parts to have lower defect rates, due to the reduced number of choices (i.e. complexity) required for their assembly. In the below tables, the number of parts in each model was averaged across all trim levels and normalized to a baseline of 1,000 parts for the dominant model.

Comparing Model A-C in Table 3.6, we observe that defect rate and number of parts for Model B are positively correlated, while for Model C they are not. This suggests that Model C suffers from a high level of transition complexity, which contributes to the elevated defect rates.

Table 3.6 - Comparison Model A-C defect rate and number of parts

Vehicle Model	Production Volume	Normalized Overall Defect Rate	Normalized Total Number of Parts
Model A	75%	1.00	1,000
Model B	20%	1.40	1,066
Model C	5%	2.82	938

We observe in Table 3.7 below that defect rate and number of parts for Models D-F are positively correlated, suggesting that transition complexity between these models is low.

Table 3.7 - Comparison Model D-F defect rate and number of parts

Vehicle Model	Production Volume	Normalized Overall Defect Rate	Normalized Total Number of Parts
Model D	51%	1.00	1,000
Model E	26%	1.11	1,181
Model F	23%	1.20	1,243

3.7 Transition Complexity Hypothesis

Comparing Model A-C and Model D-F defect rate variations over different transitions leads us to the hypothesis that transitions with a high degree of difference (i.e. magnitude of difference in familiarity, parts & processes) between the two vehicles can cause elevated defect rates. This suggests that models built on a common line should be as similar as possible, thereby reducing the Transition Complexity of the system and hence the defect rates.

Switching between two vehicles in a mixed-model assembly process can be thought of as transitioning from assembly of one complex product to another, and thus the term ‘transition complexity’ shall be used to describe this difference. The difficulty of the transition from one vehicle to another is determined by the difference in multiple factors across the vehicles, all of which increase the mental burden placed on line technicians performing the assembly tasks; i) the familiarity of the line technicians with each vehicle, ii) the difference in the part content, iii) the difference in part assembly sequence, and iv) the difference in assembly processes (tools, fixtures used, etc).

The cycle time calculated for each model should in fact account for the transition complexity that exists when switching between models on the assembly line.

3.8 Description of Factors Influencing Transition Complexity

3.8.1 Production Frequency

Increasing the production frequency of a particular model results in the plant’s workforce having a greater level of familiarity with the parts & processes required for assembly, thus reducing assembly defects.

3.8.2 Variation in Part Content

The number of parts required to assemble each vehicle varies across the models and within the variants of each model. Where there is more commonality between models, i.e. they share more parts, we would expect the Transition Complexity to be reduced as workers would be more familiar with the common parts. To complicate matters, cases exist where two vehicles share a low number of common parts, but all of the parts in each vehicle are very similar. For example, they may only have slight dimensional differences, and are therefore considered to be different part, with different part numbers and suppliers. In these cases, the Transition Complexity is low as line technicians are familiar with the similar parts in each vehicle. While the difference in part content is a factor, it effect is greatly influenced by the precise similarity between different parts.

3.8.3 Variation in Parts Assembly Sequence

The parts assembly sequence for each vehicle can vary widely, even within different versions of the same model. Nissan will typically move jobs between line segment in order to balance the workload more evenly throughout the build sequence, to avoid technicians on one segment running over time and being unable to finish their tasks. Export models often contain specific parts or additional parts due to local market regulatory requirements and as a result, their build sequence is often altered to ensure a balanced workload.

3.8.4 Relationship with Assembly Line Batch Size

The Transition Complexity that exists in an assembly system is related not only to the magnitude of the transitions between the models, but also the number of transitions (or switches) which occur. Every time we switch between models, a degree of transition complexity must be dealt with during the switch. In a mixed-model assembly system comprising two products, with only a single variant in each product, a batch size of one will provide the maximum level of transition complexity, as the number of switches is maximized. A batch size of two will half the transition complexity, all other factors being equal, as the number of switches is also halved. Similarly, a batch size of four will quarter the transition complexity and so on. Figure 3.4 below illustrates this relationship.

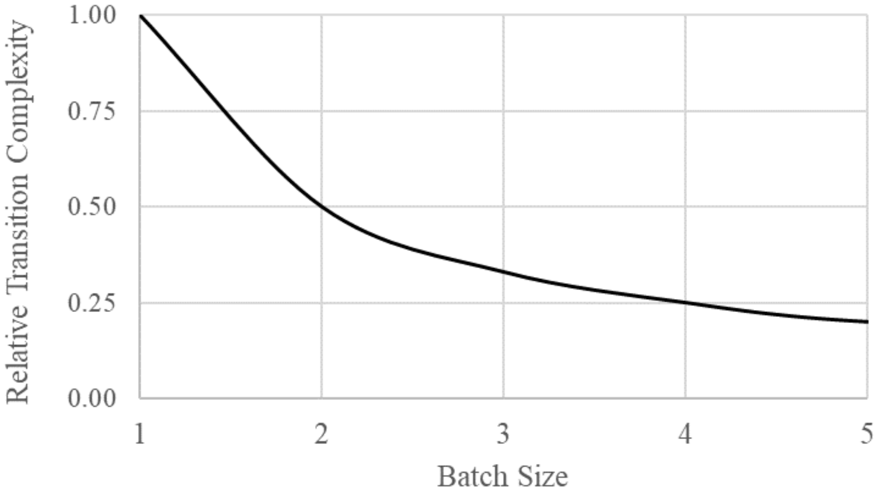

Figure 3.4 - System Transition Complexity Relationship to Assembly Line Batch Size

Chapter 4 Identifying Transition Complexity

The choice complexity defined by Marin et al. [7] takes a modified form of the Hick-Hyman Law;

$$Choice\ Complexity = \alpha(a + bH), \alpha < 0 \tag{4-1}$$

Where H is $[\ \log_2 n]$, and n is the number of alternatives (i.e. choices), here n is the total number of parts in each model assembled at the Smyrna plant. The positive scalar α serves as a weight to quantify a specific choice process [7].

This definition of choice complexity allows us to evaluate the relative choice complexity of each model built at the Smyrna plant. The normalized defect rate for each model is plotted against the H value for each model, where n is the total number of parts assembled in a single vehicle of each model at the Smyrna plant.

4.1 Choice Complexity Across Models

The choice complexity of Model A-C and D-F is compared in Figure 4.1 below. Models D-F behave as predicted by the Hick-Hyman Law; choice complexity is positively correlated with increasing H. However, while Model A & B also display this behavior, Model C does not. This leads us to conclude that transition complexity is affecting the defect rates of Model C, while for the other five models, the transition complexity could be affecting their defect rates, but not as significantly. For this reason, the remainder of this study will focus on the transition complexity of Models A-C.

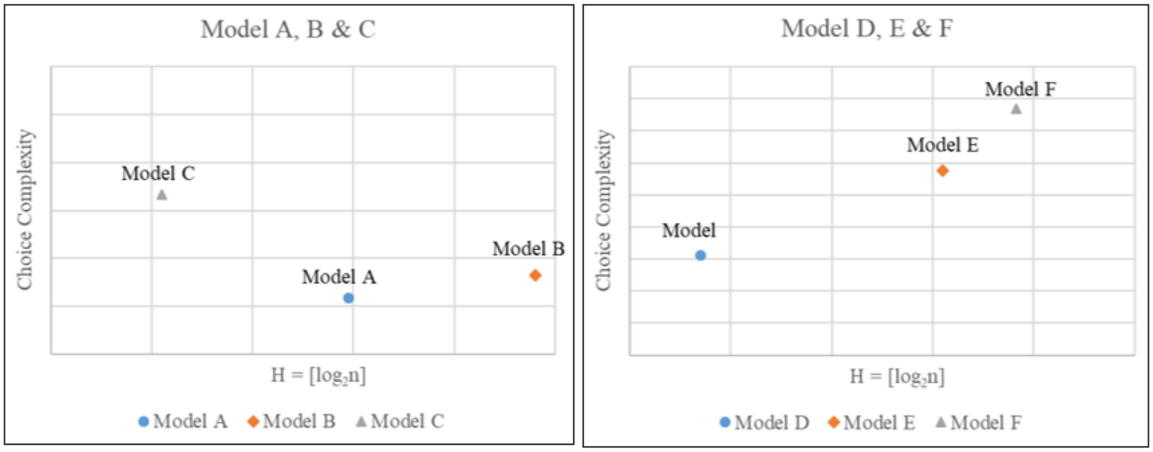

Figure 4.1 - Choice Complexity Comparison Across All Models

4.2 Choice Complexity Across Trim Levels

The relationship identified at the model level above can be expanded to the trim levels within each model. Comparing the five trim levels each of Model A & B reveals that choice complexity at the trim level is also positively correlated with H as shown in Figure 4.2 below.

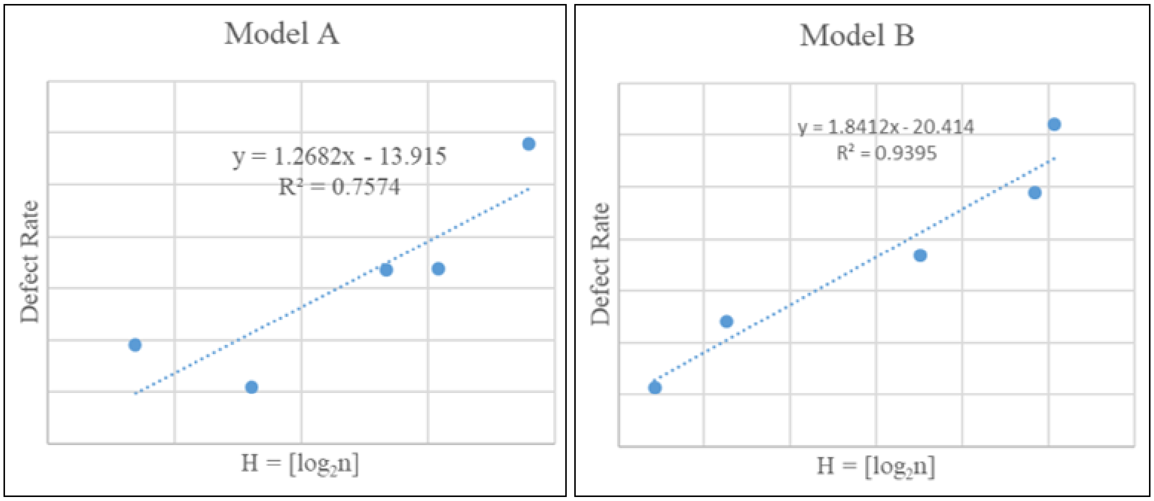

Figure 4.2 - Choice Complexity Comparison Across Trim Levels

4.3 Choice Complexity Comparison Across Model A-C

Comparing the computed choice complexity across Models A, B & C reveals that Model C does not follow the predicted behavior (choice complexity being positively correlated with H).

The much lower R^2 value of 0.37 indicates a far greater variability in choice complexity for Model C compared to Models A & B. We would expect Model A to have lower choice complexity than Model B, as it has a higher production volume and fewer parts. The greater R^2 value for Model A is a result of 5% of Model A production follows Model C, which are transitions with greater complexity, which causes more variability in the defect rates of Model A. Model B is almost always preceded by a Model A vehicle, which reduces the transition complexity for Model B, making the defect rates more predictable.

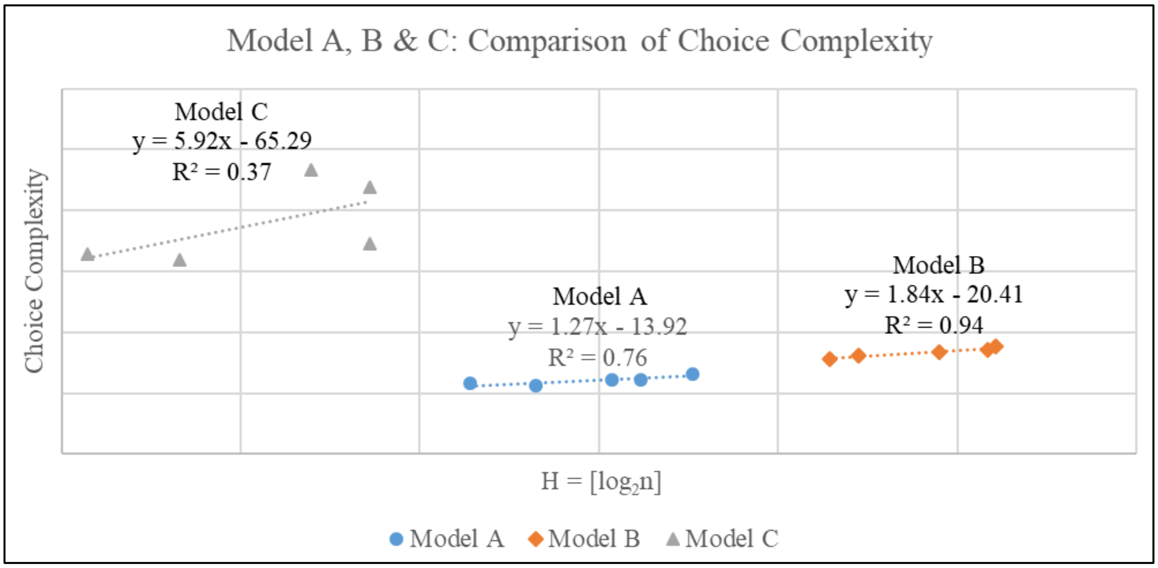

Figure 4.3 - Choice Complexity Comparison Model A-C

The elevated choice complexity observed in Model C shown in Figure 4.3 and Figure 4.4 is a result of transition complexity, where line technicians must adjust to a very different kit of parts and assembly processes between Model A and Model C. This transition complexity effectively makes choice processes more difficult for line technicians, and therefore they take longer to make the choices and have a lower probability of making the correct choice.

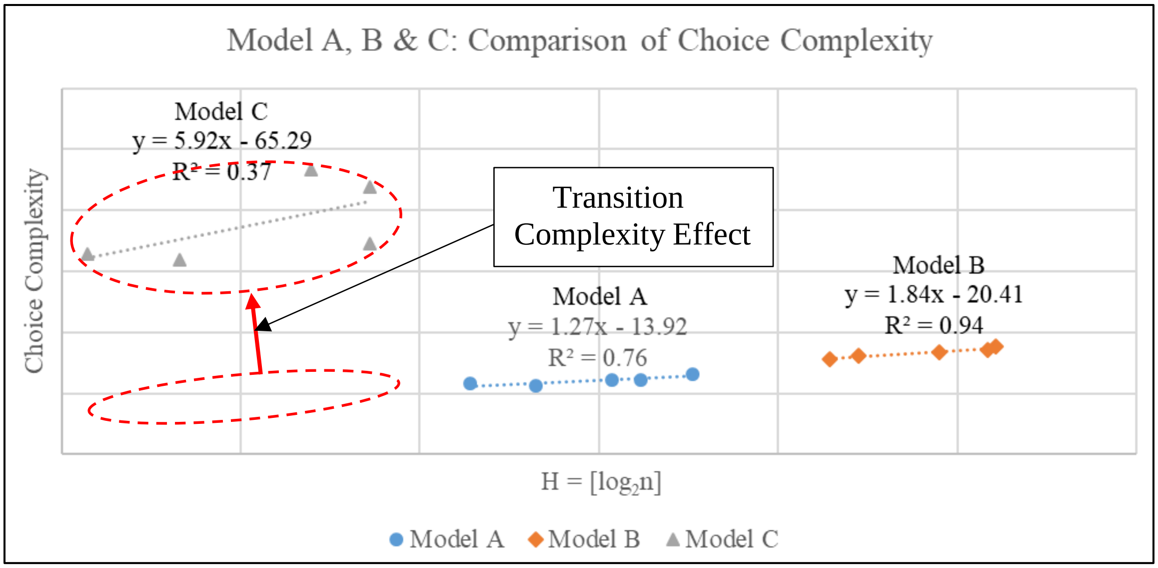

Figure 4.4 - Illustration of Transition Complexity Effect

Chapter 5 Complexity in Mixed-Model Assembly Lines (MMALs)

The Nissan Smyrna plant, built in 1983, has been progressively enlarged to accommodate a larger mix of products, and concurrently upgraded with new technology to ensure high quality even as complexity has increased. The organization understands the detrimental effect of increasing complexity on quality, and the plant's systems have been designed to control or reduce complexity where possible. This chapter shall outline an appropriate complexity framework relevant to the mixed-model assembly processes at the Smyrna plant and examine how the complexity arising from mixed-model sequencing can be quantified.

5.1 Frameworks to Evaluate Complexity

Evaluating and optimizing complexity has been an active area of research in a variety of fields including design, engineering, manufacturing and supply chain management. Hu et al, define various types of complexity in a mixed-model assembly system and propose a model of complexity to aid in the design of such systems [8].

Hu et al, define the general types of complexity in assembly systems as;

i. Choice complexity (station level) – operator choice of the correct part(s) at each station.
ii. Operator Choice complexity (station level) – operator choosing the correct fixture, tool and procedure for each part(s) at each station.
iii. Feed complexity (system level) – where choices are affected by feature variants at the current station.
iv. Transfer complexity (system level) – where downstream choices are affected by upstream choices.

We have proposed that quantifying an additional type of complexity, namely Transition Complexity, would augment the existing approach to measuring complexity in assembly systems. Transition Complexity arises when switching between different models on the same production line, as line technicians must familiarize themselves with a different set of choices for each model, both in terms of parts and assembly procedures.

Therefore, Transition Complexity can be considered a measurement of the mental burden placed on line technicians when they must accommodate variations in both i) Choice complexity and ii) Operator Choice complexity (OCC). These variations occur when technicians switch between different models on the assembly line.

Due to the structure of the mixed-model assembly system at the Smyrna plant, we will focus on the two measures relevant to station level complexity; i) Choice complexity and ii) Operator Choice Complexity (OCC). The system level complexity measures (feed and transfer complexity) shall not be addressed in this study as they are less relevant to the system configuration of the Smyrna assembly plant.

As described previously, automated guided vehicles (AGV's) deliver 'kit-carts' of parts to each segment of the assembly line. These 'kit-carts' are assembled by pickers in kitting areas, who follow an automated system that provides instructions as to which parts are required for each vehicle. This automated system largely absorbs the feed and transfer complexity, such that a line technician is not concerned with selecting parts based on the parts installed at a previous station, the technician is only concerned with installing the parts that are delivered to their station or work area.

5.2 Station Level Complexity

The framework proposed by Hu et al. allows us to qualify that the variation in station level complexity consists of four components;

1. Part Choice (component of Choice complexity) – the parts required for each vehicle vary, and the sequence in which they must be assembled could vary.
2. Fixture Choice (component of Operator Choice Complexity) – the fixtures required to install parts can vary between models.

3. Tool Choice (component of Operator Choice Complexity) – the tools required for each part (i.e. screwdrivers, torque wrench) can vary between models.
4. Procedure Choice (component of Operator Choice Complexity) – the correct assembly procedure for each part (i.e. orientation, approach angle etc) can vary between models.

We can therefore think of the variations in these four components between different models as the magnitude of transition complexity. Additionally, the familiarity of line technicians with each model can be considered a component of transition complexity, which will impact the speed and accuracy with which choices are made, and thus impacting the observed defect rate and cycle time for each model.

5.3 Complexity Drivers

Variability in each of the four components of Transition Complexity identified above will affect defect rates to a different extent. A study by Asadi et al. in a heavy machinery mixed-product assembly facility identified the relative importance of the different sources of variation on the complexity felt by assembly line technicians. The study interviewed staff at the assembly plant to produce scores for several categories of variation in the assembly process. The impact of each source was assessed on a linear scale from 1 (low impact on complexity) to 5 (high impact on complexity). Table 5.1 below shows the findings of Asadi et al, limited to factors relevant to the assembly system at the Smyrna plant.

Table 5.1 - Rating average of complexity drivers in the flexible assembly system [9]

Factor #	Drivers of complexity	Ranking Average
1	Following a common assembly sequence	5.0
2	Dissimilarities in overall product design	4.7
3	Different assembly work content	4.7
4	Use of different equipment for different products	4.5
5	High assembly workload for assembler	4.3
6	Dissimilarities of electrical interfaces	3.3
7	Use of different tools for different products	3.0

Factors with an average ranking below 3 on the complexity impact scale were not given in the study of Asadi, Jackson, and Fundin, 2016. The empirical results of this study assist in explaining the variation in defect rate observed across Models A-C and Models D-F.

In the grouping of Model A-C, Models A & B are similar in all factors, except for factors 3 and 5, which can at least partially explain the defect rate of 1.40 for Model B, compared to 1.0 for Model A. Models A & C are not similar in any factor, except for factor 5, where Model C could have a lower workload for the assemblers than Model A in some assembly areas. This can help us to understand the high defect rate of 2.82 for Model C compared to 1.0 for Model A.

We can see that where a switch between Model A and C occurs, the Transition Complexity between the two models will be influenced by at least the 7 factors outlined above. The study by Asadi et al. [9] does not explicitly assess the impact of familiarity with an individual model on quality outcomes, however familiarity with all products on an assembly line is improved if we reduce variations in factor #1 (following a common assembly sequence) and #2 (dissimilarities in overall product design) such that all products have a common assembly sequence and similar design.

5.4 De-Coupling Choice Complexity – Off-line Kitting Process

The original configuration of an automotive assembly plant was to have parts stored in racks at the side of the assembly line, and technicians in each zone would assemble parts into the vehicles as they moved along the assembly line. As the part content of vehicles increased and as OEM’s started to offer an increasing number of variants of each vehicle, technicians would spend more and more time walking along the parts storage areas to select the correct parts, until eventually the parts could no longer fit in the available space at the side of the assembly line.

The solution was to have offline part storage areas, and have a ‘kit’ of parts, specific to each vehicle on the line, delivered to the assembly line, so that technicians only select parts from the kit. This improved assembly line efficiency, (and eliminated waste) as technicians are no longer spending time selecting parts, they are focused only on assembly. However, this system necessitates having dedicated offline part storage areas with ‘pickers’ who will select the correct parts and assemble them into kits for delivery to the assembly line.

This automated system effectively splits the element of Choice Complexity in the assembly process into two distinct components;

1. ‘Selection’ Choice Complexity, where the correct parts must be selected from thousands of choices in the offline part storage area and added to each ‘kit’. The ‘pickers’ in the kitting areas handle this component of complexity.
2. ‘Sequence’ Choice Complexity, where the assembly line technicians must select parts from the kit in the correct order to be assembled correctly. There could be stations without ‘Sequence’ Choice Complexity, i.e. the order in which parts are installed does not matter.

This kitting system decouples the choice complexity and enables the line technicians to deal with a greater product variety as their complexity burden has been substantially reduced. This division of tasks allows the plant to assemble a greater variety of products, improves the efficiency of the assembly line technicians, and reduces the complexity of the assembly line tasks as line technicians only deal with the ‘Sequence’ element of the Choice Complexity. However, this system introduces an interface between the assembly line and the offline part storage areas, each of which is individually optimized to for manpower efficiency.

Referring to the Hick-Hyman Law (2.4.1), we see that reducing the number of choices for the line technicians by removing the ‘Selection’ aspect of the choice complexity will reduce complexity and hence reduce the time to complete their tasks.

5.5 Description of Sources of Assembly Process Variation at Smyrna Plant

5.5.1 Build Frequency

There is large variation in the frequency at which certain models are built, depending on vehicle demand and certain supply constraints. A certain model could be built with a frequency of 1-in-3 or 1-in-100. Export models built for overseas markets could be built to coincide with monthly shipping schedules from ports, to prevent inventory of finished vehicles occupying space at a port for an extended period.

5.5.2 Vehicle Build Sequence

As mentioned above, the vehicle build sequence is not constant and there is no batching of model production. For example, if Vehicle A has an annual average build frequency of 1-in-2, and Vehicles B & C each have an annual average build frequency of 1-in-4, there could still be cases where Vehicle A is built in a cluster of 10 or 20 vehicles in a row, and there could be instances of several hours during which Vehicle B and C are not built at all.

5.5.3 Number of Parts

There is a variable number of parts associated with each model and the trim levels within that model. The part content (i.e. not dependent on color choice) of a vehicle is dictated by the customer's choice of trim level and option packages (such as alloy wheels, enhanced stereo system and so on). A 'high' trim level variant of a model could have more electronic controls for seats and windows, and consequently there could be over 100 additional parts when compared to a 'low' trim level variant of the same model.

Due to differences in the materials and surface finish of parts, there could be hundreds of parts which are different between 'high' and 'low' trim variants of the same model. There is a larger difference in part content between the different models, due to varying size and geometry of the vehicle itself, which reduces the number of parts which can be shared across all models.

5.5.4 Parts Assembly Sequence

There are similarities in the general parts assembly sequence across Nissan's vehicles, as certain parts require special tools and fixtures for installation and must be installed at specially equipped work stations along the production line. Such parts include the engine (installed as a complete sub-assembly) and parts such as sunroof glass panels, both of which require special equipment to elevate the parts during installation.

There is also a common general order of assembly, where parts that are beneath or hidden by later parts must be installed first, for example a wiring harness (a bundle of wires for transmitting signal or power to electrical components throughout the vehicle) must be installed prior to an interior finish panel that covers it.

The general assembly sequence for each model will be common across the trim levels within that model, but there could be significant differences in the assembly sequence of different vehicles.

5.5.5 Tools & Fixtures

For each different vehicle model (and variant within the model) there is a different set of tools required to install its parts. For example, each vehicle could have different fasteners (bolts & screws) each of which has its own torque requirement, and therefore a different hand-tool might be required. Each assembly line station is permanently equipped with the tools required for the tasks at that station, so for example, a line technician may have a choice of three different hand tools.

5.5.6 Parts Delivery to Assembly Line

As mentioned above, the location of parts in the kit is variable. In the case of an infrequently built vehicle, the kit area pickers will be unfamiliar with the parts required for that vehicle, so they could take longer to complete the job and are more prone to errors. As a result, they are under greater time pressure and may not assemble the kit with the greatest care, resulting in parts being wrongly located within the kit. Parts being in a different location in the kit increases work time as the line technicians must spend longer finding the correct parts and increases the expected assembly time for the low-volume vehicle. Consequently, there is more pressure on the assembly tasks for the low-running vehicle and the vehicle built immediately after it.

5.6 Assembly Line Worker Rotations

In the Nissan Smyrna plant, line technicians rotate several times per shift to different stations along the assembly line. This rotation is performed for several reasons;

i) Ergonomics - rotating workers to different stations allow them to perform a different set of tasks and reduce repetitive strain injuries due to the overuse of certain muscle groups.

ii) Cross-training - rotating line technicians to different stations enables greater flexibility in the manufacturing operations, as they are experienced in a wider variety of tasks, which promotes mental flexibility. It also provides certain operational benefits for the plant's management, such as the ability to cover temporarily absent workers more easily.

iii) Prevents Boredom - having technicians permanently assigned to a station can increase boredom and may contribute to higher staff turnover if workers do not feel engaged in their work. Rotating workers to different stations can help to improve engagement.

As line technicians rotate between different stations, the effect of familiarity on the quality of their work is reduced. If technicians were permanently assigned to a certain station (and set of tasks) we might expect that decreasing the build frequency of certain product from 10 per hour to 1 per hour would result in a reduction in quality, as workers would rapidly lose familiarity with the tasks associated with that product. In this case, the line workers are rotating between different stations several times per shift and so they do not develop a high level of familiarity with any set of tasks.

5.7 Transition Complexity Mitigation in Product Design

From the findings of Asadi et al. [9] along with the identified sources of variation in a mixed-model assembly line, we can conclude that where multiple products are assembled on a single line, they should be as similar as possible, in terms of design architecture, parts and assembly processes. This finding is not surprising, but it does have implications for long-term production planning of manufacturing organizations like Nissan North America.

When production of different models is being planned and allocated to different plants, it is important to consider the differences between products on the same line. Where substantial differences exist, for example between Model C and Models A & B, the organization should consider changes to the design or assembly processes to better align all models on the line. In the automotive industry, the lengthy design, engineering and approval cycle will typically preclude late-stage design changes, and so assembly process changes are considered more realistic.

In the case of Model C, we have identified that high transition complexity is likely affecting defect rates. In order to give the line technicians greater adjustment time during the switch from Model A to C, the plant could perform certain sub-assembly tasks offline to reduce the time required to assemble a Model C vehicle. This would effectively reduce the assembly line workload and provide a greater amount of time for mental adjustment between models.

Chapter 6 Transition Complexity Mitigation in Kitting Systems

A substantial amount of the transition complexity in the assembly system can be attributed to design differences between models. The parts and processes required for each model reflect the design requirements and functional requirements of the target market segment, which cannot be modified at the assembly plant. An assembly plant therefore must accept that transition complexity due to these differences will occur. This chapter will focus on transition complexity arising due to the configuration of the off-line kitting system and the mitigation of this effect.

6.1 Effect of Off-Line Kitting Process

The choice complexity experienced by the assembly line technician is limited to a kit of specific parts, but the technician still must select the correct parts, in the correct sequence and install them with the correct tools according to the correct specifications. Making this series of choices correctly from the delivered kit of perhaps 50-200 parts relies on familiarity of the technician with the delivered parts and the vehicle assembly sequence.

The ease with which the technician can adapt to a different set of parts for each vehicle is related to the difference of each kit of parts compared to the dominant model on the assembly line. Even with rotations to different stations, the line technicians will develop ‘muscle-memory’ reflexes due to the time pressure they are placed under on the assembly line. If a kit of parts is delivered with different parts than they are used to dealing for 80% of the time, the line technicians must dispense with their muscle-memory reflexes and mentally recall the specific series of correct choices for this vehicle.

The most burdensome variation in choice complexity will occur when every part in the kit is different from the dominant model and therefore the mental adjustment required by the line technicians is greatest.

The choice complexity (described by Hu et al) may be split into two components to reflect this system; firstly, there is the ‘selection’ aspect of choice complexity, where the correct parts must be chosen, and secondly there is a ‘sequence’ aspect of choice complexity, where the parts must be assembled in the correct sequential order. The material (i.e. parts) handling system in use at the Smyrna plant limits the choice complexity experienced by the line technicians to only the ‘sequence’ component, thereby lessening the complexity burden at the assembly line and enabling the line technicians to assemble a wider variety of products.

6.2 Part Storage in Single-Model Assembly Lines (SMAL)

In a single model assembly line, part storage racks can be arranged next to the assembly line and line workers will choose the correct part and walk back to the vehicle to install the part. This simple configuration can work when complexity is low and the number of possible choices is limited. As the number of different models on the assembly line increases, the number of part choices increases, so line technicians have to be familiar with a greater range of parts and there subsequently a greater chance of errors in selection. This general configuration in shown in Figure 6.1 below.

In addition to this, line technicians also have to cover a greater distance as the part storage racks will increase in size, resulting in more wasted time walking back and forth. As the assembly plant’s range of products continues to increase, there will be space constraints at the side of the assembly line, where there is physically not enough space to store all the parts. The assembly plant must either be enlarged or a more efficient system must be devised.

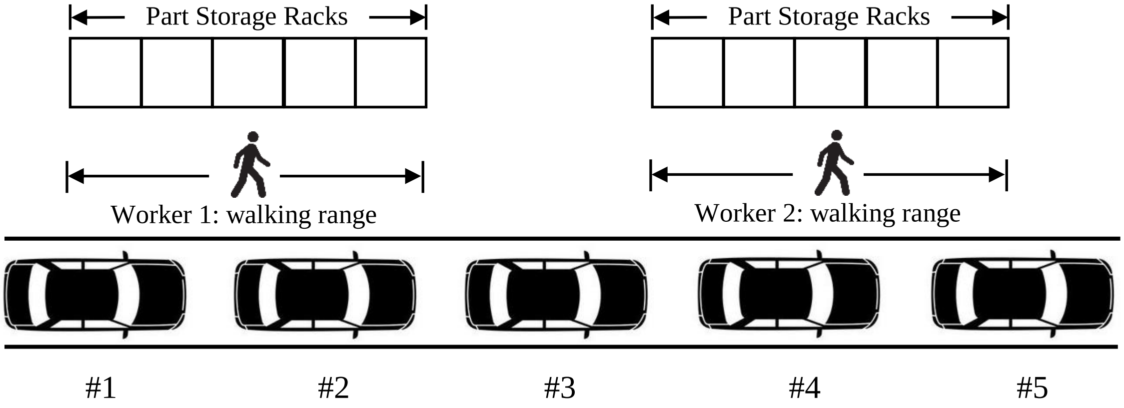

Figure 6.1 - Part Storage Configuration in SMAL

6.3 Part Storage in Mixed-Model Assembly Lines (MMAL)

As plants transition mixed-model production and manufacture a greater variety of vehicles, it becomes necessary to have systems that deliver the necessary parts for each vehicle to the assembly line. At the Smyrna facility, a ‘kit’ of parts is assembled in an off-line storage area and delivered to the assembly line. The kit travels down the assembly line with the vehicles and will pass through the working range of several workers who will install the specific parts.

This eliminates the ‘selection’ component of the choice complexity from the line technicians, such that they only deal with the ‘sequence’ component of the choice complexity, if any exists (the specific assembly sequence may or may not matter at each station on the assembly line). This configuration is shown in Figure 6.2 below.

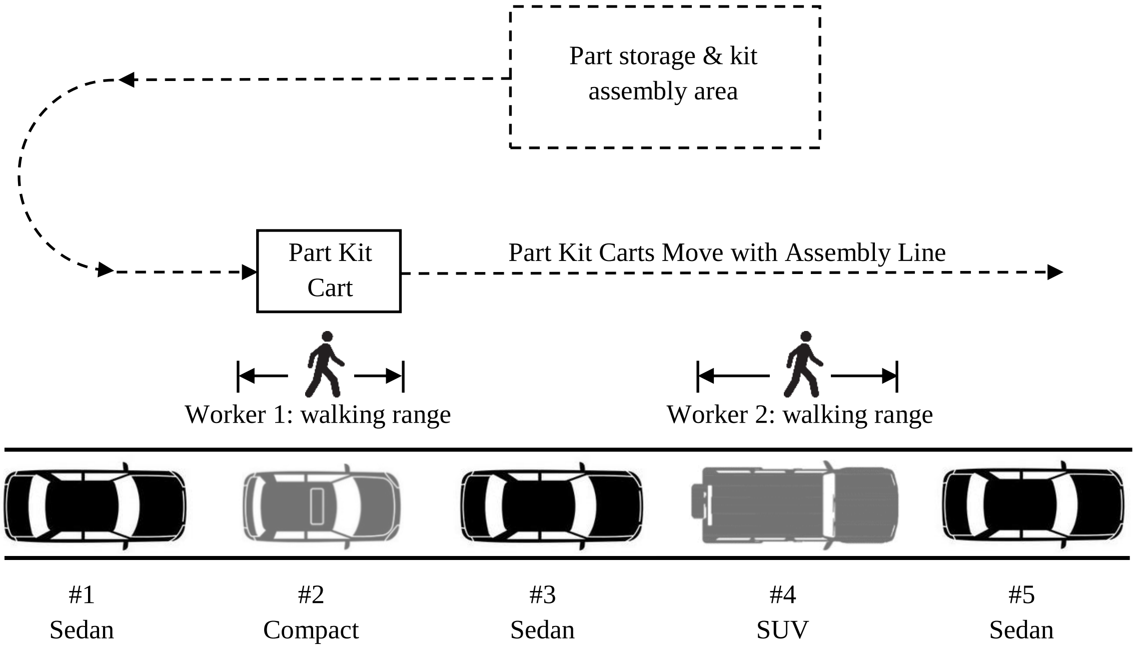

Figure 6.2 - Off-Line Part Storage Configuration in MMAL

6.4 Configuration of Part Storage & Kit Assembly Areas

Although this solution allows the plant to deal with the increased complexity associated with manufacturing more vehicles, it adds an interface between two separate areas, each of which is optimized to minimize waste. In this new system, the part storage & kit assembly area is optimized to reduce manpower requirements, so the walking distance is minimized. This means that high frequency parts are arranged close to the kit cart and low frequency parts are arranged further away, such that a kit cart for a high-volume vehicle is quicker to assemble than one for a low-volume vehicle.

Whilst this makes sense from a cost optimization standpoint, in practice it means that the kit cart assemblers take longer to assemble a kit cart for a low volume vehicle, causing more stress during the part picking process which can lead to the kits being more hastily assembled. This effect can lead to parts being placed in wrong locations in the kit, meaning that assembly line technicians spend longer identifying the part they require, which increases the vehicle assembly cycle time, which increases the stress of performing the assembly work, and this in turn can lead to a greater number of errors during assembly.

In addition to this, the parts being picked are parts with which the pickers are less familiar and therefore there is a greater chance of a mis-pick where the wrong part is chosen, and so when the assembly line technician receives the kit, they notice that a part is not correct, and this must be rectified. Usually someone is sent to manually retrieve the correct part from the pick area, and the correct part is installed at the end of that line section, or at some other point further down the assembly line.

This effect results in the kit carts for low volume models being assembled with more variability in part placement, which leads to low-volume models having a greater cycle time than the designed cycle time as line technicians will take longer to identify the correct part. This means that the technicians must 'catch-up' time on the vehicle being assembled after the low-volume model, which will result in them working faster to install the required parts in a shorter length of time.

To exacerbate this, there are also large differences in part content and build sequence so part pickers in the kitting areas may not be familiar with where to place the parts for a low-volume model in a kit cart, as the parts being installed at that point in the sequence at different from the high-volume models.

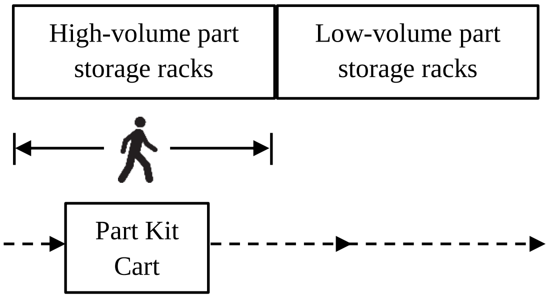

Figure 6.3 - Diagram of Part Picker Working Range for High Volume Model

Figure 6.3 above shows the part storage and kit assembly area, where the high-volume parts are grouped together, so that the part 'pickers' are more efficient and spend most of their time only in the 'High-volume' area. This reduces the average amount of time (and steps) taken to assemble an average kit cart, and therefore reduces the manpower required to a minimum. However, when a cart comes enters the area for a low-volume vehicle, the part 'pickers' now have to cover a much larger area to retrieve the required parts. There is part sharing across high and low volume models, so a low volume vehicle will generally share some parts from a high-volume vehicle, requiring the part picker to cover a greater range, and be faced with the same amount of time to assemble the kit cart.

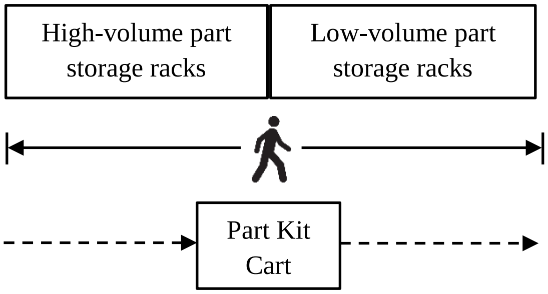

Figure 6.4 - Diagram of Part Picker Working Range for Low Volume Model

The average time allotted to the assembly of the kit cart is the same for both high and low-volume vehicles, but with the above configuration shown in Figure 6.4 we can see that assembling the kit cart for the low-volume vehicle will be more challenging, due to the greater distance covered, and the unfamiliarity with the low-volume parts. This compounded effect leads to kit carts for low-volume vehicles having potentially higher rates of wrong parts, and the parts within the kit may not be positioned correctly, so even if the cart has all the correct parts, they may be in the wrong slots as the part ‘pickers’ are under more stress to complete the part picking process.

When the kit cart arrives at the assembly line, the line technicians must spend longer locating each part in the kit, which adds extra time to their assembly tasks. It increases the difficulty of making the correct choices. This cascading effect means that the assembly time for a low-volume vehicle will often be longer than the calculated cycle time, which then means line technicians have to ‘catch up’ a greater amount of time on the subsequent vehicle.

6.5 Errors from Kitting Process

The offline kitting process used to enable MMAL at the Smyrna plant can cause a range of defects to be passed from the part storage area to the line technicians. The part pickers deal with the selection aspect of choice complexity and can pass errors in the kit carts to the line technicians, who will then log a defect in the in-plant system and then have to waste time rectifying the error. As mentioned above, given the configuration of the kitting areas, we expect the low-volume models to have a greater rate of kitting errors.

6.5.1 Types of Kitting Errors

The most common types of errors from part picking areas are i) the kit is missing a part, ii) an extra part has been mistakenly added to the kit and iii) the wrong part is in the kit.

Kitting errors are typically rectified very easily by having someone manually go to the kitting area, select the correct part and deliver it to the assembly line. There could be other categories of kitting error in the defect data set, but based on error descriptions, it can be difficult to discern errors due to kitting and due to other causes.

6.5.2 Comparing Kitting Errors across Models

Comparing the kitting errors across Model A-C in Table 6.1 below, we observe a negative correlation between the production volume and the kitting errors reported. This finding can partially explain why Model B & C vehicles have a higher defect rate than Model A.

Table 6.1 - Summary of Kitting Errors for Model A-C

Vehicle Model	Production Volume	Normalized Kitting Error Rate	Normalized Overall Defect Rate
Model A	75%	1.00	1.00
Model B	20%	2.48	1.40
Model C	5%	3.57	2.82

The normalized kitting error rate of 2.48 for Model B is far greater than the overall normalized defect rate of 1.40, suggesting that kitting errors are a major contributor to the increased defect rate. Similarly, the kitting error rate of 3.57 for Model C is far greater than the overall normalized defect rate of 2.82, suggesting that kitting errors are a major contributor to increased defect rate we observe for this Model. Figure 6.5 below visualizes the relationship between build volume and kitting errors.

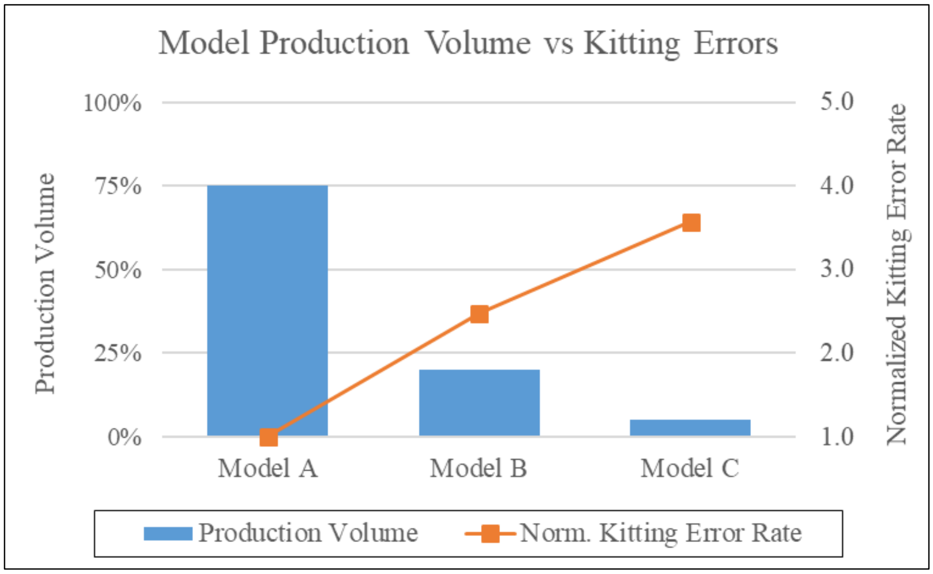

Figure 6.5 - Visualization of Kitting Errors and Production Volume, Model A-C

The increase in kitting errors will lead not only to an increased defect rate, but also an increase in actual cycle time to assemble each vehicle. For example, in the case of a missing part, the line technician will perform the following steps; 1) notice the part is not in the correct place, 2) search the whole kit for the part, 3) call for the correct part to be expedited from the kitting area. Performing these three steps can take up valuable time on the assembly line and be severely disruptive to the thought process of a line technician.

6.5.3 Comparing Kitting Errors across Trim Level

The relationship of kitting error and production volume applies to the trim levels within each model. The below figure illustrates the negative correlation between the production volumes of the six trim levels within Model A and kitting error rate. Model A data was selected as it contained a large number of data points for a robust comparison.

Although trim level 4 in the below Figure 6.6 shows a lower defect rate than trim level 3, this could be due to the forecasted build volume for 4 being higher than 3, and therefore the parts for 4 were advantageously positioned within the kitting area compared to 3.

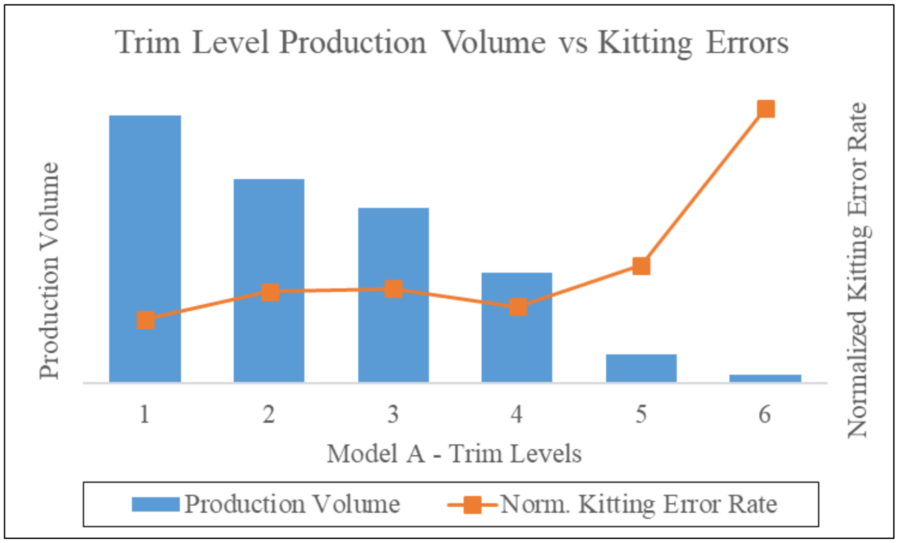

Figure 6.6 - Visualization of Kitting Errors Across Model A Trim Levels

This relationship displays the advantage of reducing the number of trim levels within each model; even within a model with high production volume, the kitting errors are sensitive to the production volume of the trim levels within the model. Reducing the trim levels would logically increase the production volume of each trim level, thereby reducing kitting errors and reducing overall defects. This shows the advantage of product rationalization at the assembly plant and avoiding production of trim levels with very low production volumes.

Kitting errors increase defect rates, particularly in low-volume models, where they can have a substantial effect. Kitting errors increase the actual cycle time on the assembly line, and this partly explains the increased defect rate of Model A vehicles preceded by Model C vehicles. The actual cycle time for Model C vehicles is increased due to kitting errors, which leads to higher defect rates on the vehicle itself and affects the following vehicle on the assembly line.

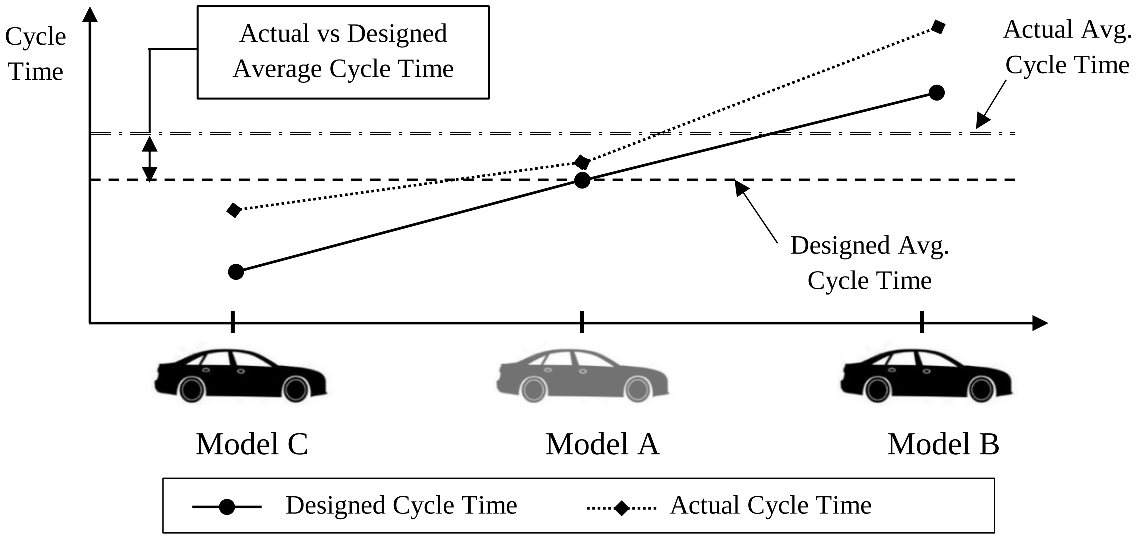

Figure 6.7 - Diagram of Effect of Kitting Errors on Cycle Time

In Figure 6.7 above, the practical effect of transition complexity from kitting errors is shown; these errors increase the actual cycle time for Model B & C vehicles and potentially the ⅓ Model A vehicles preceded by Model B & C. This effect increases the average cycle time on the assembly line and could lead to a degradation in overall system performance as the cycle time is above the designed expectation and hence the production rate could be set unrealistically high.

6.6 Recommendations to Mitigate Kitting Errors at the Smyrna Plant

The move to an offline kitting system enabled the Smyrna plant to accommodate a greater product variety by reducing the complexity burden on line technicians. However, there remains the possibility of errors, especially at the interface between the kitting area and the assembly line. The kitting errors observed may be reduced by the following measures;

6.6.1 Modify Design of Offline Part Storage Areas

The layout of the off-line part storage areas could be modified so they are optimized to reduce defects, rather than being optimized to reduce manpower requirements. From a cost perspective, optimizing to reduce manpower is the dominant consideration, however this comes at the cost of reducing overall quality outcomes, as low volume models are penalized in the current system. The part storage areas could be modified so that low-volume parts are mixed with high-volume parts, which would increase the average time to complete a kit but could lead to preferable quality outcomes when considering the benefit to the line technicians.

6.6.2 Implement a ‘Smart’ Vision System

A vision system which makes use of machine learning could help to detect kitting errors before kit-carts leave the kitting area. This system would be similar to those already in use at the Smyrna plant. This vision system would look vertically downwards onto the cart and check if slots in the kit cart are empty, or if they are filled with the wrong part. The sequencing system in use at the Smyrna plant would allow this system to know which vehicle the kit cart is destined for, and therefore the system would know what the parts should look like.

Chapter 7 Transition Complexity Mitigation in Production Scheduling

Production scheduling can influence the defect rates of vehicles assembled at the Smyrna plant. In the initial observations of defect rates, it was observed that Model D-F exhibited a more regular production pattern than Model A-C and the effect of production regularity has been further investigated. This chapter compares the defect rates observed during two different production periods, focusing primarily on Model C.

7.1 Defect Rate Summary for Second Production Period

A second production period for the Model A-C assembly line was chosen during period 2018-19. The production volume, defect rate and average sequence gap are given in Table 7.1 below.

Table 7.1 - Summary of Model A-C Defect Rates for Second Production Period

Vehicle Model	Production Volume	Normalized Overall Defect Rate	Average Sequence Gap Between Models
Model A	80%	1.00	0.3
Model B	13%	1.53	6.2
Model C	6.5%	2.64	11.7

We observe a reduction in Model C defect rate from 2.82 previously to 2.64, a reduction of 6%. The defect rate of Model B has increased from 1.40 to 1.53, an increase of 9%. We could attribute these differences to the variation in production volume, however in this period, the average choice complexity of the Model C (i.e. number of parts per vehicle) has increased as more premium trim levels versions were produced, indicating that the cycle time for an average Model C vehicle has increased.

Table 7.2 - Effect of Preceding Vehicle on Model A Defect Rate in Second Production Period

Dominant Model	Preceding Vehicle on Assembly Line	Normalized Defect Rate
Model A	Model A	1.00
	Model B	1.01
	Model C	1.07

In Table 7.2 above, we see the effect of Model C on the following Model A vehicle has reduced from 1.13 to 1.07, indicating that the transition complexity has reduced in this period. The average cycle time during the second production period is likely to have fallen slightly, due to the 7% reduced volume of Model B vehicles, and only a slight increase in Model C vehicles of 1.5%. This reduced cycle time on the assembly line may also be contributing to the reduced effect of Model C vehicles on the following Model A, since line technicians are under less pressure.

There was a small improvement in kitting errors of less than 2.8% between the two periods, indicating that improvement in kitting errors is not the principal reason for the reduction in defect rate in Model C.

7.2 Comparison of Production Frequency

7.2.1 Model C

The average sequence gap for Model C in the second production period was much lower than in the first period, and we observed a reduction in defect rate of 6% in the second production period. Comparing the sequence gap frequency over the two periods, we observe that in the second production period 54% of Model C had a sequence gap of 8 or less, compared to 22% of Model C vehicles in the first production period. This suggests that Model C vehicles in the second period were being produced either with low sequence gaps, or not at all.

Figure 7.1 below compares the frequency of sequence gap in the two periods, up to a gap value of 35. There were a significant number of sequence gaps observed above 35, but these have not been included.

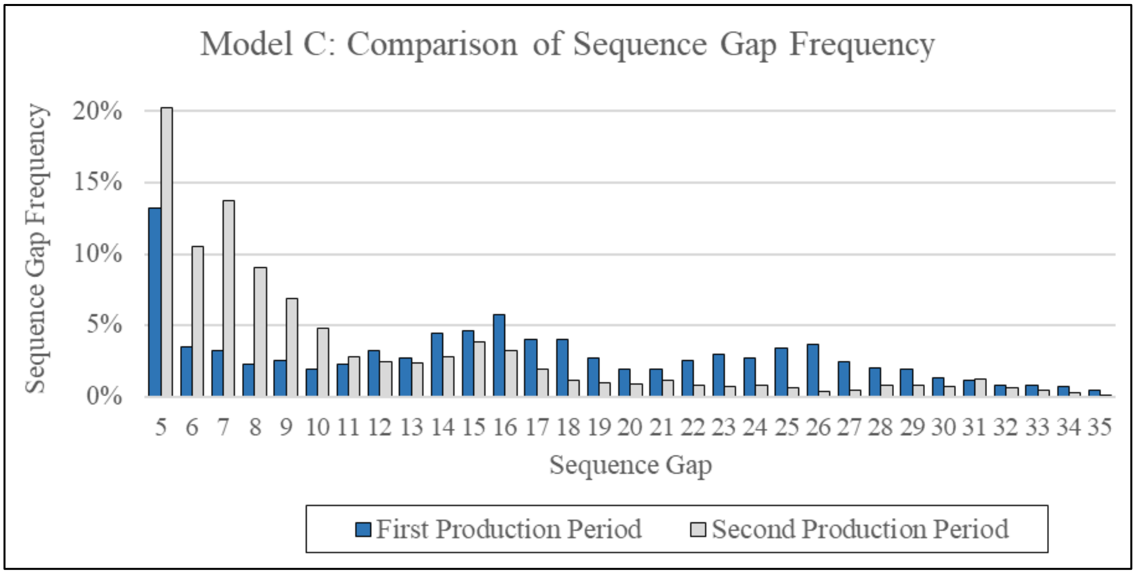

Figure 7.1 - Comparison of Model C Sequence Gap Frequency

The sequence gap frequency in the second production period was more concentrated towards the lower sequence gaps and this factor may have had an effect on reducing the transition complexity, and thus lowering the defect rate of Model C. The increased regularity of Model C production in the second period is similar to the production behavior observed in Model D-F.

7.2.2 Model B

The average sequence gap for Model B in the second production period was greater than in the first period, and we observed a 9% increase in the defect rate of Model B in the second production period. Comparing the sequence gap frequency over the two periods, we find that in the first production period 91% of Model B had a sequence gap of 6 or less, compared to 56% of Model B vehicles in the second production period having a sequence gap of 6 or less.

Figure 7.2 below compares the frequency of sequence gap in the two periods, up to a gap value of 20. There were a significant number of sequence gaps observed above 20, but these have not been included. The sequence gap frequency in the first production period of Model B was more concentrated around lower sequence gaps of less than or equal to 6, this factor may have had the effect of reducing the transition complexity in the first production period due to the regularity of the transition.

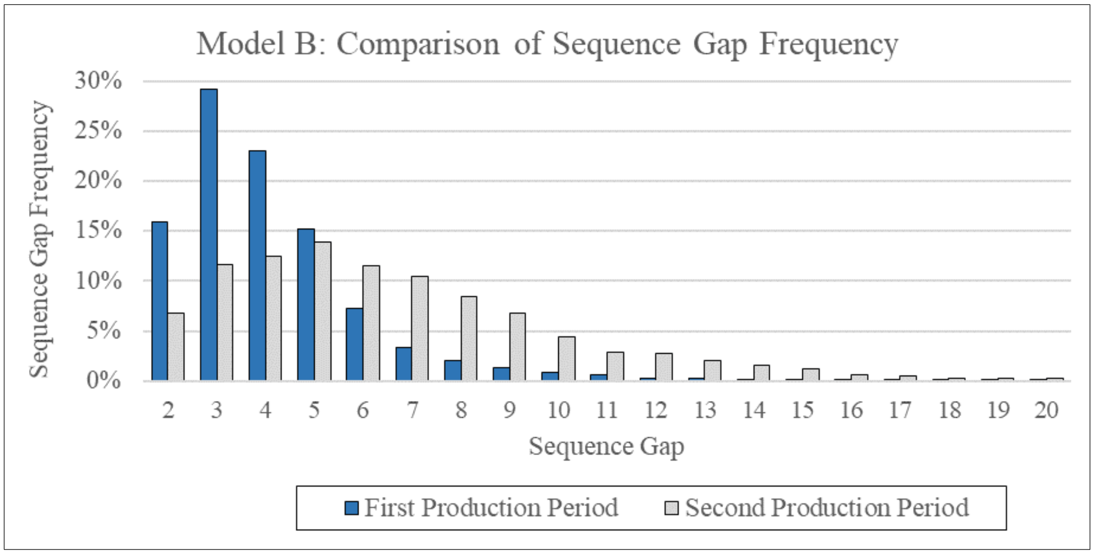

Figure 7.2 - Comparison of Model B Sequence Gap Frequency

It is clear in the above Figure 7.1 and Figure 7.2 that we can expect reduced defect rates where sequence gap frequency is more concentrated at the lower range. The defect rate for Model B was lower in the first production period when sequence gaps were concentrated in the range of 2 to 6. Similarly, the defect rate for Model C was lower in the second production period when there was greater concentration of sequence gaps in the range of 5 to 10. We expect the reduced defect rates are a result of improved regularity in production, where line technicians and part pickers can establish a more regular rhythm in their work.

7.3 Scheduling Recommendations to Reduce Transition Complexity

Given the above comparison in Model B and Model C sequence gap frequencies, it is advisable to modify the current scheduling methodology to improve defect rates. The current scheduling constraints are applied as upper limits on build frequency, for example, a constraint may limit the production of Model C to no greater than 1-in-5, as appears to be the case in the figure above.

The scheduling constraints could additionally have a minimum constraint of perhaps no fewer than 1-in-10 for Model C and no fewer than 1-in-6 for Model B. This constraint could be enforced at the beginning of the day (or shift), such that in the case of Model C, vehicles will be produced with a frequency of between 1-in-5 and 1-in-10, until production of Model C is no longer required. Therefore at the end of the day (or shift), the assembly line is only producing Model A & B, and production of Model C will not restart until the next day.

Chapter 8 Conclusions

Transition complexity is an important consideration when optimizing the performance of a mixed-model assembly system. Manufacturing organizations should consider the transition complexity which arises between different products when they perform early-stage product design and engineering, and when they allocate production to different assembly plants.

Once identified, transition complexity can be mitigated by adjusting the assembly processes for each model, for example, an assembly plant could perform a greater number of sub-assembly tasks offline, to allow assembly line technicians more time to adjust to model transitions.

8.1 Offline Kitting Process Recommendations

In modern assembly plants, where offline kitting processes are used to reduce assembly line complexity, care must be taken to ensure that kitting defects are not passed to the assembly line, particularly for low volume vehicles. To mitigate such effects, assembly plants could implement the following measures;

8.1.1 Modify Design of Offline Part Storage Areas

The layout of the off-line part storage areas could be modified so they are optimized to reduce defects, rather than being optimized to reduce manpower requirements. The part storage areas could be modified to mix high-volume and low-volume parts, which would increase the average time to complete a kit but could lead to preferable quality outcomes.

8.1.2 Implement a 'Smart' Vision System

A vision system which makes use of machine learning could help to detect kitting errors before kit-carts leave the kitting area. This system would be similar to those already in use at the Smyrna plant. This vision system would look vertically downwards onto the cart and check if slots in the kit cart are empty, or if they are filled with the wrong part. The sequencing system in use at the Smyrna plant would allow this system to know which vehicle the kit cart is destined for, and therefore the system would know what the parts should look like.

8.2 Production Scheduling Recommendations

The sequencing aspect of a mixed-model assembly appears to be important, and the author recommends that scheduling strategies which improve the quality of low-volume products are used where possible. Where the mixed-model sequence followed a more regular, repeating pattern, superior quality outcomes were achieved.

The scheduling constraints could additionally have a minimum constraint of perhaps no fewer than 1-in-10 for Model C. This constraint could be enforced at the beginning of the day, so that all Model C vehicles will be produced with a frequency of between 1-in-5 and 1-in-10, until production of Model C is no longer required, so that at the end of the day the assembly line is only producing Model A & B, and production of Model will not restart until the next day.

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