

Improving Parts Delivery through Data Aggregation, Analysis, and Consumption

by

David Engel Amiot

B.S., United States Military Academy, 2008

Submitted to the Department of Mechanical Engineering and the 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

in conjunction with the Leaders for Global Operations Program at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2018

© David Engel Amiot, MMXVIII. All rights reserved.

The author hereby grants to MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part in any medium now known or hereafter created.

Signature redacted

Author
Department of Mechanical Engineering and the MIT Sloan School of Management
May 11, 2018

Signature redacted

Certified by
Steven Spear, Thesis Supervisor
Senior Lecturer, MIT Sloan School of Management

Signature redacted

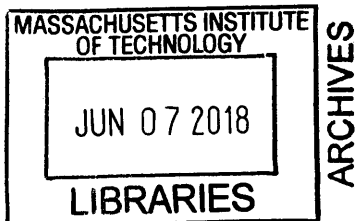
Certified by
Daniel Whitney, Thesis Supervisor
Senior Research Scientist Emeritus, MIT Leaders for Global Operations,
and Senior Lecturer, Mechanical Engineering

Signature redacted

Accepted by
Dhan Abeyaratne
Chairman of the Committee on Graduate Students, Department of Mechanical Engineering

Signature redacted

Accepted by
Maura Herson
Director, MBA Program, MIT Sloan School of Management



Improving Parts Delivery through Data Aggregation, Analysis, and Consumption

by

David Engel Amiot

Submitted to the Department of Mechanical Engineering and the MIT Sloan School of Management on May 11, 2018, in partial fulfillment of the requirements for the degrees of
Master of Science in Mechanical Engineering
and
Master of Business Administration

Abstract

Data analytics and visualization are topics of significant interest in the business and manufacturing communities. This research investigates the hypothesis that, if production floor managers consume properly analyzed data, then their ability to solve problems and prevent production system disruptions improves. This research tests this hypothesis through simulation and a pilot program on Boeing's closet fabrication line and identifies the types of data managers require to improve their operations.

The closet fabrication line struggles to complete orders on time, and this problem serves as the central focus for this research. A root cause analysis indicates that issues delivering parts to the closet fabrication line contribute to this problem. Given this issue, this research applies data analysis and visualization tools to facilitate the process improvements required to solve the parts delivery problem.

This analysis supports the validity of the initial hypothesis. The results of the discrete event simulation predict an 11% decrease in the time required to fabricate a closet and a 50% decrease in the number of days late the production line delivers closets. The pilot program yields an 11% reduction in build duration and a 32.5% decrease in the duration of the average late completion, while increasing the percentage of complete kits delivered from 39.4% to 80.0%. While the pilot program encompasses a small data set of ten closets, it provides an initial validation of the hypothesis. These results also indicate that information regarding warehouse inventory status, the production queue, and the priority of orders in the queue are valuable data that managers require to improve manufacturing performance.

Thesis Supervisor: Steven Spear

Title: Senior Lecturer, MIT Sloan School of Management

Thesis Supervisor: Daniel Whitney

Title: Senior Research Scientist Emeritus, MIT Leaders for Global Operations,
and Senior Lecturer, Mechanical Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

Acknowledgments

While there are too many people to thank for the assistance I received over the last year of research, I would like to acknowledge several individuals for their efforts and unwavering support.

First, I would like to thank Juan Lopez and Adam Marshall for developing this project and supporting me from the internship interviews all the way to the final draft of the thesis. This research would not have been possible without their help and guidance and their insights and assistance proved invaluable.

To the everyone in the AC&S team, and especially Hyun Ah Lim, Janice Hinson, John Yu, Jack Merrill, and Michel Claessens, I cannot thank you enough for your patience and support as I navigated Boeing's data systems and developed my analysis. I learned much from my time in AC&S and I had a great time being part of the team.

To the closet shop leadership team, especially Dan McQueen, Rich Oberg, James Scott, and Scott Martin, thank you for your never-ending patience and for answering my endless list of questions. Without your help, this project would not have happened, and I certainly had fun working with your team and learning the challenges of manufacturing from the people that know them best.

To the Boeing LGO community, in particular Tom Sanderson, Lizzie Hammer, Liz Ugarph, Dave Haas, and Andrew Byron, thank you for all the tours and connecting me with all the right people. Exploring Boeing was not only fun, but also provided the inspiration for much of this research.

Turning to the MIT community, I would like to extend a special thanks to my advisors, Dan Whitney and Steve Spear, whose mentorship and guidance not only helped me through this project, but also taught me many valuable lessons along the way. Thank you for all of your thoughtful advice and insights, I could not have asked for a better team. Lastly, a special thanks to the LGO Class of 2018 for all the support, encouragement, laughs, and adventures.

THIS PAGE INTENTIONALLY LEFT BLANK

Contents

List of Figures	14
List of Tables	16
List of Abbreviations	17
List of Symbols	19
I Project Background and Current State Analysis	21
1 Introduction	23
1.1 Project Origin and Statement of Purpose	23
1.2 Problem Statement and Hypothesis	24
1.3 Problem Solving Approach	25
1.4 Thesis Overview	26
2 Project Background	27
2.1 The Virtual Moving Line Concept	27
2.1.1 Historical Context	27
2.1.2 Present Day Challenges	28
2.2 Initial State of the Project	29
2.2.1 The Closet Fabrication Line	29
2.2.2 Initial Research and Prototype	30

3	Current State of the Closet Fabrication Line	33
3.1	Fabrication Process Background	33
3.2	Problem Identification through Root Cause Analysis	35
3.3	Current State Analysis Methodology	36
3.4	Results of the Current State Analysis	36
3.4.1	Interview Findings	36
3.5	Conclusions and Motivation for Future Research	45
4	Benchmarking Best Practices	47
4.1	Kitting Background	47
4.2	Challenge: Build Kits with Existing Systems	47
4.3	Benchmarking Methodology	48
4.4	Key Findings and Benchmarking Results	48
4.4.1	Parts Availability	48
4.4.2	Scheduling and Sequencing	49
4.4.3	Evaluation Incentives	50
4.4.4	Successful Kitting Strategies in Different Environments	51
4.5	Conclusions	51
 II Developing and Testing Solutions through Discrete Event Simulation		 53
5	Improving Supply Chain Visibility through Discrete Event Simulation	55
5.1	Background of Supply Chain Visibility and Improved Communication	55
5.2	Discrete Event Simulation Background	57
5.3	The Probability Distribution Requirement	58
5.4	Process Logic Development Methodology	59
5.5	Data Analysis and Distribution Fitting	60
5.6	Results and Distribution Selection	61
5.7	Conclusions	61

6	Validation of the Discrete Event Simulation	63
6.1	Validation Requirement and Background	63
6.2	Validation Challenges	63
6.3	Simulation Validation Methodology	64
6.4	Data Utilized for Validation	66
6.5	Results of the Validation Process	67
6.6	Conclusions	68
7	Testing Prioritization Methods using the Discrete Event Simulation	71
7.1	Background	71
7.2	Selecting the Proper Prioritization Method	73
7.3	Methodology for Comparing and Evaluating Prioritization Methods	73
7.4	Comparison and Evaluation Data	74
	7.4.1 Prioritization Methods and Techniques	74
	7.4.2 Testing the Prioritization Methods through Simulation	76
7.5	Results	76
7.6	Conclusions	79
8	Testing the Impact of Improved Kit Delivery on Production System Performance	81
8.1	Simulating Improved Kit Delivery	81
8.2	Simulation Challenges	81
8.3	Improved Kit Delivery Evaluation Methodology	82
8.4	Distribution and Regression Data Inputs	83
8.5	Simulation Results	86
8.6	Conclusions	87
III	Testing Proposed Solutions on the Production Floor	89
9	Selection of Process Changes for Pilot Program Testing	91
9.1	Pilot Program Background and Intent	91

9.2	Pilot Program Requirements and Limitations	91
9.3	Pilot Program Methodology	92
9.3.1	Parts Delivery Methods: Push versus Pull	92
9.3.2	Improving the Decision Making Process	94
9.3.3	Evaluation Metrics	95
9.4	Results and Conclusions	96
10	Developing Digital Visibility and Communication Tools	97
10.1	Background	97
10.2	Visibility Tool Problems to Solve	98
10.3	Visibility Tool Development Methodology	98
10.4	Solutions Developed to Support the Pilot Program	99
10.5	Results	101
10.6	Conclusions	101
11	Pilot Program Development and Execution	103
11.1	Pilot Program Execution Background	103
11.2	Pilot Program Challenges and Limitations	103
11.3	Execution Methodology	104
11.3.1	User Roles and Responsibilities	104
11.3.2	Pilot Program Execution	106
11.4	Data Collected during Pilot Program	106
11.4.1	Data Collection Plan	107
11.4.2	Consolidated Data Findings	107
11.5	Results and Analysis	108
11.5.1	Initial Observations	108
11.5.2	Hypothesis Test Results	111
11.6	Conclusions	113
12	Simulation and Pilot Program Results Comparison and Findings	115
12.1	Results Comparison Background and Motivation	115

12.2 Problem to Solve	115
12.3 Results Comparison Methodology	116
12.4 Comparison Data	116
12.5 Findings and Results	116
12.6 Conclusions	119
13 Key Results and Conclusions	121
13.1 Review of Research Background and Goals	121
13.2 The Parts Delivery Problem	121
13.3 Key Results and Conclusions	122
13.3.1 Information Improves Decision Making	122
13.3.2 Limited Link between Data Access and Urgency	123
13.3.3 Proper Fundamentals Matter	123
Glossary	125
A Current State Analysis Plots	127
B Distribution Fitting Plots	131
Bibliography	141

THIS PAGE INTENTIONALLY LEFT BLANK

List of Figures

2-1	Example of a commercial airplane closet	29
2-2	Initial VML prototype	31
3-1	Closet fabrication process diagram	34
3-2	Fish bone diagram for root cause analysis	37
3-3	Relationship between dates that drive closet scheduling	38
3-4	”Five whys” process for root cause analysis	41
3-5	Closet completions, January 2016 to September 2017	42
3-6	Closet completions for Program A aircraft, January 2016 to September 2017	43
3-7	Monthly closet deliveries, January 2016 to September 2017	44
3-8	Density distributions for missing parts and days late for Program A aircraft	45
3-9	Linear regression of late completions vs missing parts, June to November 2017	46
5-1	Comparison of probability distribution fits for Program A closet final assembly process	61
6-1	Comparison of actual and model build duration results	66
6-2	Comparison of actual and model late completion results	67
7-1	Visual example of slack time determination	75
7-2	Comparison of probability distributions for build durations, all prioritization methods	77
7-3	Comparison of probability distributions for late completion days, all prioritization methods	78

8-1	Linear regression of late completions vs missing parts, June to November 2017	83
8-2	Probability distribution fitting for parts missing per closet	84
8-3	Simulation results for improved kit delivery	86
9-1	Parts delivery via push system	93
9-2	Parts delivery via pull system	94
9-3	Current kit request and delivery method	95
9-4	Proposed kit request and delivery method	96
10-1	Dashboard depicting the prioritized production queue and inventory status .	99
10-2	SharePoint site to request kit deliveries	100
11-1	Comparison of build durations before and during the pilot program	108
11-2	Comparison of late completion days before and during the pilot program . .	109
11-3	Pilot program and simulation results	110
12-1	Pilot program and simulation results	117
A-1	Current state of late deliveries, all airplane programs	128
A-2	Current state of stocked out parts, all airplane programs	128
A-3	Current state of missing parts, all airplane programs	129
A-4	Current state of total missing parts, all airplane programs	129
B-1	Probability distributions for Program A sweep and sand process	132
B-2	Probability distributions for Program A tab and slot process	133
B-3	Probability distributions for Program A final assembly process	134
B-4	Probability distributions for Program A fabrication process total duration . .	135
B-5	Probability distributions for Program B sweep and sand process	136
B-6	Probability distributions for Program B tab and slot process	137
B-7	Probability distributions for Program B final assembly process	138
B-8	Probability distributions for Program B fabrication process total duration . .	139

List of Tables

3.1	Missing parts analysis for the current state of operations	45
4.1	Challenges and best practices found during benchmarking process	51
5.1	Distribution parameters for the Program A final assembly	60
6.1	Results of t-test for build duration results, actual vs simulated	68
6.2	Results of t-test for late completion results, actual vs simulated	68
7.1	Hypothesis test results for build duration	78
7.2	Hypothesis test results for late completion days	79
11.1	Pilot program standard work and execution sequence	105
11.2	Closet build durations before the pilot program	107
11.3	Key characteristics of closets built during the pilot program	108
11.4	Mean and standard deviation of key performance metrics	110
11.5	Percent of complete kits and associated completion days late	111
11.6	Pilot program hypothesis test results	112
12.1	Build duration improvement, simulation and pilot program results	118
12.2	Days late improvement, simulation and pilot program results	119
B.1	Distribution parameters for Program A sweep and sand process	132
B.2	Distribution parameters for Program A tab and slot process	133
B.3	Distribution parameters for Program A final assembly process	134
B.4	Distribution parameters for Program A total duration	135

B.5	Distribution parameters for Program B sweep and sand process	136
B.6	Distribution parameters for Program B tab and slot process	137
B.7	Distribution parameters for Program B final assembly process	138
B.8	Distribution parameters for Program B total duration process	139

List of Abbreviations

- BOM** Bill of Materials. 39, 47, 56, 99, 100
- DES** Discrete Event Simulation. 57, 58, 64, 73, 76, 81, 83, 85, 86, 95, 117–119, 122
- ERP** Enterprise Resource Planning. 28, 48, 51, 72
- FF-A** Fabrication Facility A. 24, 25, 29, 30, 33–35, 39, 40, 46, 48, 50, 58, 84, 87, 92, 94, 95, 97, 99, 104
- FF-B** Fabrication Facility B. 48–52
- FF-C** Fabrication Facility C. 48–51
- FIFO** First In, First Out. 58, 74, 75
- LIFO** Last In, First Out. 58
- MPR** Manufactured Parts Request. 42, 43, 84, 107, 111, 112
- MPRF** Manufactured Parts Request Facilitator. 40
- SOS** Source of Supply. 40, 42, 107, 111, 112
- TPS** Toyota Production System. 27
- VML** Virtual Moving Line. 23–30, 35, 36, 46, 48, 51, 52, 56, 71, 81, 91, 100, 104, 109, 113, 122, 123
- WIP** Work in Process. 38, 92, 121

THIS PAGE INTENTIONALLY LEFT BLANK

List of Symbols

- β Percent change in the number of complete kits delivered to the closet fabrication line
- Δ Change in closet build duration associated with a change in the percent of complete kits delivered to the closet fabrication line
- x Number of parts missing from a closet kit
- y Number of days late a closet order is completed

THIS PAGE INTENTIONALLY LEFT BLANK

Part I

Project Background and Current State Analysis

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 1

Introduction

The Boeing Company (Boeing) is a market leader in aircraft and space system design and manufacturing. With over 100 years of aerospace experience, the company boasts an impressive resume filled with industry firsts. However, as information technology evolves and the ability to store and utilize data becomes more common, the company desires to take advantage of its large data repositories and provide factory managers with the information they need to improve manufacturing operations. The following research investigates the value of data analysis and visualization in a manufacturing environment and identifies what data managers require to improve their operations.

1.1 Project Origin and Statement of Purpose

This research originates in a concept known as the Virtual Moving Line (VML), which seeks to generate the benefits of a physically moving production line by leveraging data analysis and visualization. The VML concept states that properly analyzed and displayed data provide the feedback and situational awareness managers require to identify problems in the production system, anticipate future disruptions, and take initiative to improve manufacturing operations. While moving production lines provide many of these benefits, it is difficult to move large items, such as commercial airplanes, which drives Boeing's desire to achieve these results while the items in production remain stationary.

The VML is Boeing's methodology to achieve this goal through data analysis, visualiza-

tion, and consumption. This research tests this idea by analyzing the flow of parts between two nodes in Boeing’s supply chain and identifies the data required to execute the VML concept. By developing a detailed understanding of the production system’s current state, modeling the impact of specific changes to the system, and testing these changes in a factory environment, it is possible to assess the validity of the VML concept, identify the data required to implement the concept, and provide recommendations for further research.

1.2 Problem Statement and Hypothesis

Boeing’s Fabrication Facility A (FF-A) fabricates a wide range of interior components for all of Boeing’s commercial airplane programs. This facility produces overhead stow bins, cabin partitions, crew rest areas, closets, carpets, and many other items. These items are key components of a commercial airplane’s interior, and for an airline, the interior is the centerpiece of a passenger’s experience. Given the importance of an airplane’s interior, Boeing strives to provide interior components that meet each airline’s exact requirements. However, this dedication to customer satisfaction comes with a challenge: the more options Boeing provides its customers, the more variability exists in the interiors fabrication process. This variability creates numerous challenges and makes tasks such as procuring and stocking the correct parts, training mechanics, and establishing standard work more difficult. The result is a less efficient manufacturing system.

The FF-A closet production line is an excellent example of this variability. The production line fabricates more than 100 closet models and supports the final assembly lines for every commercial airplane model. In addition, there are over 600 decorative schemes available to the airline customers. This variability leads to significant challenges delivering the correct parts to closet fabrication mechanics. As a result, these mechanics often lack the parts they require to fabricate closets.

This project considers the parts delivery problem and utilizes the VML methodology to implement the required process improvements. This research hypothesizes that if the production queue is visible to both the production line and its supporting warehouse, the production queue is organized in a prioritized manner, and communication increases between

supply chain nodes, then the percentage of complete kits arriving in the closet fabrication line increases. It is expected that improving parts delivery leads to shorter closet build times and fewer late completions. To achieve these communication and visibility improvements, this project develops data visualization tools that link the VML concept to manufacturing process improvements. These tools serve as a test of the VML concept.

1.3 Problem Solving Approach

To test this hypothesis and improve parts delivery in the FF-A, this research progresses through three phases. The first phase is an analysis of the current state of the closet fabrication process. Developing a detailed understanding of the closet fabrication line's requirements, its current performance, and the challenges its managers face both informs solutions and provides a baseline to evaluate changes in the production system's performance. This phase includes direct observation of the production line, interviews with managers, team leaders, mechanics, industrial engineers, supply chain analysts, and manufacturing engineers, as well as a quantitative analysis of production system data. This phase's key areas of interest are the flow of parts and material through the production system, the time required to complete each process in the fabrication process, and the impact missing parts have on process times and completion delays.

After assessing the current state of the production system, the second phase focuses on simulating the production process. This phase requires the development and validation of a simulation and an assessment of key changes to the production system. Analyzing the impact of each change on the production system's performance informs which changes and new tools are tested on the production floor during phase three. In addition, the theoretical results generated in the discrete event simulation provide a benchmark to evaluate the effectiveness of changes made on the production floor.

The final phase consists of a pilot program to implement and test the changes recommended by the results of the discrete event simulation. This pilot program runs for a defined period of time, and allows for a comparison between the results of the pilot program, the results of a control group, and the results produced by the discrete event simulation. Com-

paring these results and testing for statistically significant changes in the production system's performance allows for an evaluation of the previously stated hypothesis.

1.4 Thesis Overview

This thesis contains three parts that relate to the three phases of the research project. Part I develops and analyzes the current state of the closet fabrication line and provides the basis for a quantitative analysis of the impact of future changes to the production system. Part II develops a discrete event simulation that evaluates changes to the production system and recommends actions to test during a pilot program on the production floor. The final part of the thesis details the development of digital communication tools to make the supply chain visible to managers, discusses the parameters for an eight day pilot program, reports the results of the pilot program, and draws conclusions regarding the validity of the VML hypothesis.

Each chapter in this thesis serves as a discrete learning cycle, in which background information are collected, a problem is identified, a methodology is selected to solve the problem, the supporting data are gathered, results are developed, and conclusions are drawn. Each chapter maintains this background/problem/methodology/data/results/conclusions format with the intention of allowing the reader to enter the document at any point and understand a learning cycle of interest. In addition, this methodology communicates the learning cycles that occurred during the six-month research period and provides the reader with a feel for the evolution of this project.

Chapter 2

Project Background

2.1 The Virtual Moving Line Concept

The VML concept is a method to drive problem solving and improve operational performance through data analysis, visualization, and consumption. The concept hypothesizes that providing production floor managers with easily accessible and consumable data allows them to make better decisions, solve problems before they occur, and synchronize the people, parts, processes, and tools required to execute operations in an efficient manner. In addition, the VML concept seeks to accomplish this goal by utilizing existing production system data only, rather than creating new data sources and the associated collection mechanisms.

2.1.1 Historical Context

From a historical perspective, this concept is not new to Boeing. The company has implemented numerous lean initiatives in the past, and its lean journey is ongoing. From kitting improvements, to visual control systems, to an assembly line that physically moves airplanes through the final assembly process, Boeing has experimented with many methods to generate a sense of urgency in the manufacturing process. Boeing has applied many of the Toyota Production System (TPS) principles to aircraft manufacturing with the goal of creating a sense of urgency in the work force, simplifying parts delivery, and standardizing work.

The Program B¹ final assembly line provides an excellent example of Boeing's efforts to implement lean principles in the manufacturing process. In an effort to generate the urgency needed to maintain takt time, Program B delivers parts to mechanics in kits designed to support a two hour work package. *Flight Global* describes the process as follows:

Mobile robotic carts will begin replacing human workers shuttling parts and tools to machinists assembling Boeing [Program B aircraft] in Everett, Washington. Each automated cart will bear kits loaded with precisely enough gear to occupy a machinist for 2h. As each kit is exhausted, the mobile assistant will reappear with a fresh kit, restarting the machinists' 2h clock.[10]

This effort aims to achieve the same goals as the VML concept and benefits from the realization that moving airplanes during final assembly is quite difficult, but creating a sense of motion and urgency can be achieved through other means. In this instance, the Program B assembly line creates a sense of movement by increasing the frequency of parts delivery. The VML concept intends to create this sensation through data analysis and visualization.

2.1.2 Present Day Challenges

Many of Boeing's current Enterprise Resource Planning (ERP) tools provide production system status to the user; however, this information is difficult to access and interpret. In addition, the information needed to inform a decision often resides in multiple data systems, which requires a user to access several tools to create a complete picture of the production environment. The VML seeks to overcome these challenges by synthesizing key information from multiple data sources and providing the user with a simple, yet complete, set of relevant data in a single interface. By referencing this single interface, users become aware of the production queue and the status of the people, parts, processes, and tools required to manufacture the items in the queue.

¹Airplane program names are anonymized throughout this research to protect proprietary data.

2.2 Initial State of the Project

This research builds on a previous effort to generate an initial VML prototype and test it in a production environment. The initial VML prototype creates a digital representation of the production floor and makes this representation available to production managers, manufacturing engineers, and supply chain analysts. To develop and test this initial prototype, the VML team worked with the FF-A and utilized the closet fabrication line as a test bed for this concept.

2.2.1 The Closet Fabrication Line

The closet fabrication line produces closets for commercial airplanes. These closets have numerous uses, including storing passenger outerwear during flights, electronic equipment, safety devices, or food. Figure 2-1 depicts a typical commercial airplane closet.

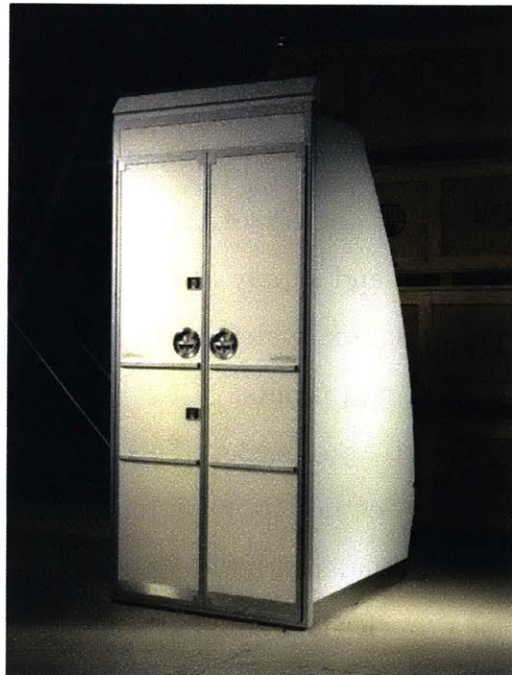


Figure 2-1: Example of a commercial airplane closet
Photo from Airline Suppliers website [11]

While the closets themselves seem simple, their fabrication process and variability make these items an excellent candidate for researching the VML concept. Boeing excels at offering airline customers with a wide range of interior options and unique decorative schemes. While

this wide range of options provides superior service to the airline, it leads to highly variable demand in the production system. This environment creates opportunities to test the VML concept and provide managers with the data required to improve decision making.

The closet fabrication line utilizes three main processes to produce a closet. The first phase, known as sweep and sand, ensures that the exterior panels are smooth and ready for the application of the decorative scheme, if required. During this phase, a mechanic applies a decorative laminate to the exterior components. The second process, known as tab and slot, prepares the exterior panels for assembly and ensures the proper fit between the closet's main components. The final phase is assembly. The assembly process takes the prepared panels and other components and produces the completed closet. During this time, all of the required parts must be delivered to the mechanic and a series of manual processes are executed until the closet is complete. Chapter 3 provides a detailed overview of the closet fabrication process and its current state.

2.2.2 Initial Research and Prototype

The initial VML prototype depicts the three phases of the fabrication process in a digital environment to provide increased awareness of the production system's current state to managers, manufacturing engineers, and supply chain analysts. This initial prototype tests the hypothesis that existing production system data is robust enough to provide useful information without requiring new data inputs.

Figure 2-2 depicts the first VML prototype. This prototype indicates where a closet is in the production system, provides details regarding whether the closet is on pace to be completed on time, and what manufacturing defects, known as non-conformances, have been identified. This prototype provides two important insights regarding the VML concept. First, the prototype proves that it is possible to utilize existing production system data to generate a digital depiction of the production environment. The second insight is that production system personnel find the information useful. The FF-A manufacturing engineers that support the closet fabrication line are not located with the production line, which requires them to commute to the production line to gather data. Providing this data through a digital tool provides convenient data access, which the manufacturing engineers find useful.



Figure 2-2: Initial VML prototype

This research builds on these findings and tests the hypothesis detailed in Chapter 1.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 3

Current State of the Closet Fabrication Line

3.1 Fabrication Process Background

The closet fabrication process consists of manual processes to prepare materials for assembly, receive parts, assemble kits, and complete final assembly. These activities occur in three steps and require seven to ten days to complete. Many items arrive at the FF-A as raw materials and the FF-A processes these materials to produce closet wall panels, doors, and other components. This research focuses on the processes that occur on the closet fabrication line, and does not consider the raw material processing steps undertaken by other production lines within the FF-A.

Before detailing the fabrication process, it is critical to understand the anatomy of an airplane closet. As depicted in Figure 2-1, the closet consists of side walls, one or more doors, an exterior laminate that matches the airline's interior decorative scheme, and a variety of fittings, trims, and other components. The closet fabrication line receives these parts, executes a variety of finishing tasks, and completes the final assembly tasks. The side walls and doors consist of a honeycomb panel cut to shape by the FF-A using three and five axis routers. The FF-A produces decorative laminate using a silkscreen process that produces a wide variety of designs. The remaining parts are produced by internal suppliers (wiring harnesses, for example) or procured from outside vendors (brackets, door

knobs, trim, and many more items). The closet fabrication line receives parts from the FF-A supply chain and produces kits for the mechanics on the production floor. Each kit includes panels, decorative laminate, and detail parts. The FF-A's three and five axis router area delivers panels to the closet fabrication line, the silkscreen area delivers the laminate, and the FF-A's internal warehouse delivers kits that contain the details parts.

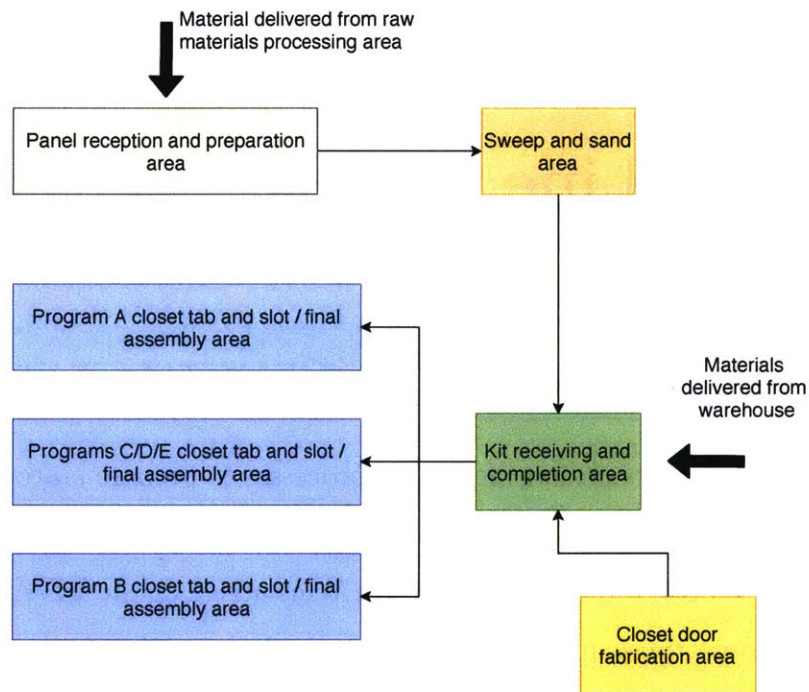


Figure 3-1: Closet fabrication process diagram

Figure 3-1 details the flow of components through the closet fabrication line. Prior to the sweep and sand phase, exterior panels and other items are cut to the proper size and prepared for assembly by drilling holes, inserting fasteners, and cutting tabs to facilitate the final assembly process. Once these preparatory tasks are complete, the closet fabrication line receives the panels and prepares them for assembly during the sweep and sand phase. The sweep and sand phase removes any excess epoxy from the panel, smooths the panel surface, and removes any remaining dust from the cutting process. At the end of the sweep and sand phase, the panels receive the decorative laminate produced in the FF-A's silkscreen area. This laminate ranges from a simple film to an elaborate carpet, and may require the use of a variety of tools ranging from a roller and press to a vacuum bag system. Once the exterior

panels receive their laminate, they are ready for the next step.

The tab and slot process receives the prepared panels, fits the panels together, and in some instances, applies epoxy to bond the panels together. Once a closet enters the tab and slot phase, the closet is placed on a work bench and a single mechanic executes the majority of the work until the closet is complete. The work completed during the tab and slot phase varies by aircraft and closet model. Once the tab and slot process is complete, the final assembly process begins. During final assembly, the exterior fittings, electrical components, sealants, and other items are attached to the closet. In some cases, decorative laminate may also be applied to certain areas during final assembly.

While the fabrication process requires a limited number of steps, the demand variability that exists in the FF-A is one of several factors that complicate closet fabrication. The closet fabrication line copes with variable demand by assigning a closet build to a specific mechanic and having that mechanic complete the closet from start to finish, rather than assigning specific tasks to specific work stations. Variability also creates challenges for the supply chain. Few of the closets produced are alike, which causes few of the kits and parts required to build the closets to be alike. The result is the need to build unique kits for many of the closet orders, which reduces the warehouse and kitting area's ability to use standard tools like shadow boxes to ensure the required parts are present in a kit.

3.2 Problem Identification through Root Cause Analysis

To test the VML hypothesis, it is necessary to identify a specific problem, understand its root cause, and develop a method to remedy the root cause using the VML concept. Following interviews with fabrication line managers and team leads, the issue of late closet completions becomes the problem of interest for the root cause analysis. The frequency with which this issue arises leads to an initial conclusion that the closet fabrication line struggles to complete closets on schedule, and requires the use of overtime labor to deliver closets to its customers (the customer is generally the aircraft final assembly line, although the line does produce

some closets for aftermarket sale).

Determining and quantifying the current state of operations on the closet fabrication line begins with a series of interviews and progresses to a quantitative analysis. The initial interviews focus on production floor managers, team leaders, mechanics, industrial engineers, and manufacturing engineers. These individuals provide a wide variety of input that guides the quantitative analysis. The quantitative analysis utilizes production system data to confirm the interview findings, provide numerical values for those findings, and creates an initial benchmark against which to measure the impact of future changes.

3.3 Current State Analysis Methodology

The current state analysis utilizes the A3 problem solving process and historical production system data to assess the magnitude and frequency of late closet completions. Density distributions provide a visual method to analyze the data, while average values and the percent of closet orders delivered late and missing parts provide summary statistics of the current production environment. The final step is determining whether a correlation exists between missing parts and late closet completions. A linear regression model provides an initial investigation into this correlation.

3.4 Results of the Current State Analysis

Figure 3-2 summarizes the key findings made during the qualitative phase of the root cause analysis and identifies behind schedule closet completions as the initial problem to solve. This analysis indicates that part shortages are a root cause of the late closet completion problem. As a result, improving the delivery of parts to the closet fabrication line becomes the central problem to solve with the VML methodology.

3.4.1 Interview Findings

Interviews with production floor managers, team leaders, and mechanics indicate several clear trends.

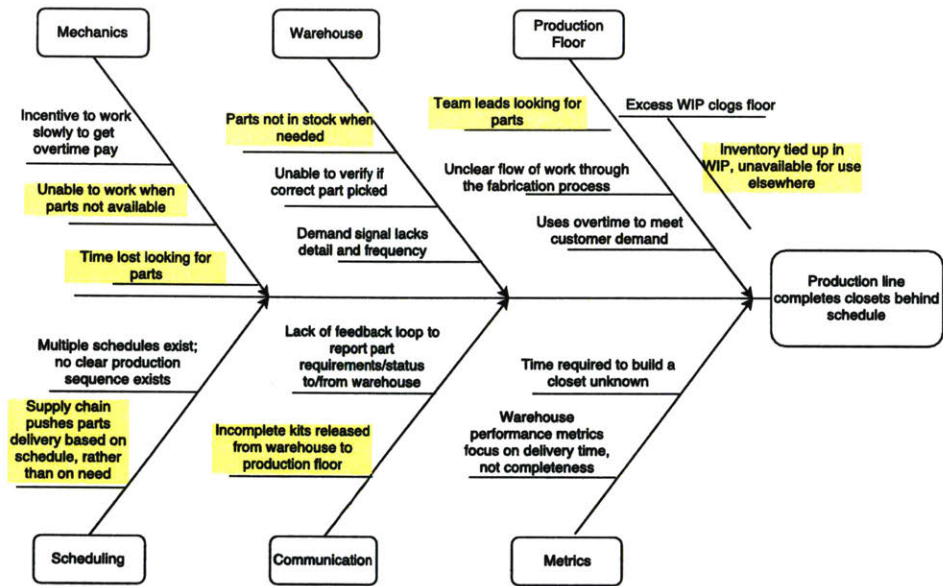


Figure 3-2: Fish bone diagram for root cause analysis
The issues involving parts are highlighted in yellow

Scheduling Challenges

The first key observation is the lack of clarity regarding when a closet order must be completed. The production floor utilizes several different schedules to control its work. The first schedule utilizes the date that a closet is scheduled to be loaded onto an aircraft in final assembly. This date, known as the "load date," is the date that the closet must be available at the aircraft final assembly line. If the closet is not available at this time, the final assembly process will be impacted. This date flows from the final assembly schedule set by the airplane program industrial engineers.

The second schedule reports a completion date that reflects when the production floor should complete a closet order. These completion dates are set by the closet fabrication line's industrial engineering team and reflect the expected time required to complete a closet order. Industrial engineers derive the closet order completion dates by finding a closet order's load date, adding a buffer time of five days, and then adding the expected build duration time. From there, the closet fabrication line's industrial engineer staggers the completion dates to create a completion schedule in which the production floor completes two closets per airplane program, per day. This system serves as a scheduling heuristic and has no connection to the production line's takt time.

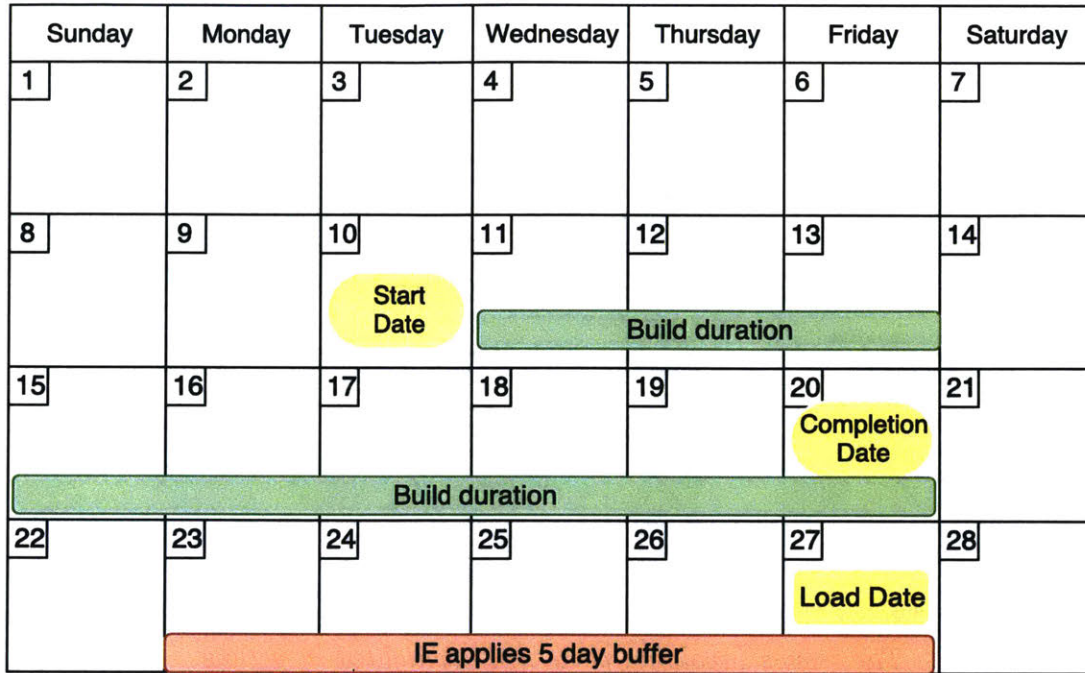


Figure 3-3: Relationship between dates that drive closet scheduling

In this example, the aircraft final assembly line requires the closet to be available on Friday the 27th. The industrial engineers add a five day buffer window and schedule the production line completion date for Monday the 22nd. A ten day build duration establishes a start date on Tuesday the 10th. While these three dates are linked, an opportunity for confusion arises when multiple dates are in use for productions scheduling.

The final schedule relies on closet build start dates. These start dates reflect the completion schedule described above and indicate when a specific closet order should be started. The start dates dictate when parts are delivered to the closet fabrication line by other nodes in the supply chain, the order in which closets are built, and dictates how much time is available for a closet to be built before its schedule completion time. Figure 3-3 provides a visual depiction of these dates and how they relate to one another.

While a series of common dates link these three production schedules, the presence of multiple schedules creates confusion and allows the management team to focus on finishing closets prior to the required airplane load date, rather than maintaining a consistent schedule that meets the production floor's takt time. The combination of the seasonal demand, the presence of excess Work in Process (WIP) on the production floor, and the highly variable nature of production orders creates an environment where systems become reactive to crisis rather than grounded in sound operations principles.

In addition, the industrial engineers set start dates well in advance of the closet's actual start date, which leads to a series of problems with parts delivery. As conditions on the production floor change, the previously assigned start dates are not updated, which compounds problems that arise on the production line. Confusion also arises when the closet fabrication line is behind schedule and begins to execute its work based on closet load dates (the most critical of the three dates), but the warehouse supporting the line continues to utilize the planned start dates to deliver parts.

There are several actions tied to a closet's start date. The closet start date informs the FF-A warehouse which closets will be built when, and what parts must be delivered. Each closet has a Bill of Materials (BOM) the warehouse must deliver as a kit prior to the start of the closet fabrication process. The warehouse picks these parts from inventory, places the parts in a clear plastic bag, and then delivers the bag to the production floor one day prior to the closet build's start date (these kits contain the previously mentioned detail parts). This process assumes the closet builds start on schedule, and the warehouse receives notification of the start dates five days prior to the scheduled start date. This process appears practical at first, but it does not take into account changes made by the production floor managers to react to problems or delays in the fabrication process. If a closet's actual start date occurs after its planned start date, the warehouse continues to deliver parts to the production floor on the original schedule. This action leads to several consequences. First, inventory begins to build in the closet fabrication kitting area. Second, there are excess kits present on the production floor that are not being utilized. Finally, the build up of excessive inventory allows parts to become lost or re-allocated to fill parts shortages in other kits. Multiple interviews confirmed that these problems lead to confusion and are a source of disruption on the closet fabrication line.

Parts Delivery Challenges

Another key finding from the interview process is the discovery of issues delivering parts to the production floor. In addition to the late completion problem, the subject of missing parts and incomplete kits arises on numerous occasions. Mechanics, team leaders, and managers report that the production floor and kitting area struggle to receive complete kits from the

warehouse. These incomplete kits may be missing one or more parts, and in some instances, these missing parts delay the start or completion of a closet order. In addition, a mechanic may source a missing part from one of the excess kits delivered to the production floor by the warehouse, which spreads the problem to other orders. To alleviate this problem, a Manufactured Parts Request Facilitator (MPRF) coordinates the request and delivery of missing parts (or in some instances, returning parts delivered in excess). The development of a job function to overcome parts shortages indicates that this problem is not only common on the closet fabrication line, but also exists throughout the company.

The reports of missing parts and the presence of the MPRF lead to further investigation regarding the parts delivery process. Interviews with warehouse parts pickers and managers indicate that the FF-A warehouse focuses on delivering kits to its customers one day prior to a job's scheduled start date. However, the warehouse does not focus on delivering a kit that has all of the required parts. Frequent observation of kit paperwork indicating a part is not available during the picking process (known as a stocked out or Source of Supply (SOS) part) lends credibility to these anecdotes and leads to a more rigorous quantitative analysis of this issue.

These interviews also uncover the possibility that the parts delivery process may be a root cause of the late closet completion problem. Figure 3-4 depicts the "five whys" process associated with the parts delivery challenge. This diagram highlights the depth of the parts shortage problems and suggests several initial solutions (these solutions are discussed further in Parts II and III). Given these findings, the quantitative analysis proceeds to confirm or deny these initial deductions.

Verifying the Late Completion Observations

The quantitative analysis begins with an assessment of how many closets are completed after the scheduled completion date determined by the production line's industrial engineer. If a closet's actual completion date is after its planned completion date, the closet is considered late. This tardiness has the potential to drive the need for overtime labor, lead to disruptions in the production schedule, and cause disruptions or delays on the aircraft final assembly line. Plotting a density distribution of the number of days late for closet completions for all

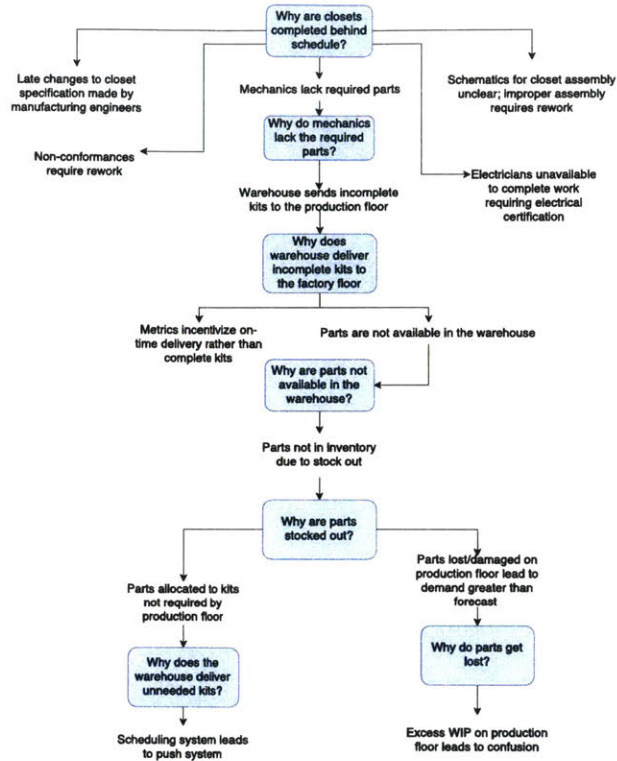


Figure 3-4: "Five whys" process for root cause analysis

closets produced indicates that the vast majority of closets are completed behind schedule.

The density distribution in Figure 3-5 indicates a clear presence of late closet completion. On average, closets are completed 4.1 days behind schedule. To confirm this trend further, a similar analysis considers only closets for Program A aircraft. This airplane has a high production rate and leaves little room for error in closet delivery to the final assembly line.

Figure 3-6 indicates that the pattern of late completions holds true for Program A closets. In addition, of the 192 closet orders produced for Program A aircraft between August 1, 2017 and October 31, 2017, 20 were completed on time or early, and the remainder were completed after their scheduled completion date, resulting in 89.6% of closet orders being completed behind schedule. This evidence indicates that late closet completions do exist and confirms the interview process's qualitative findings.

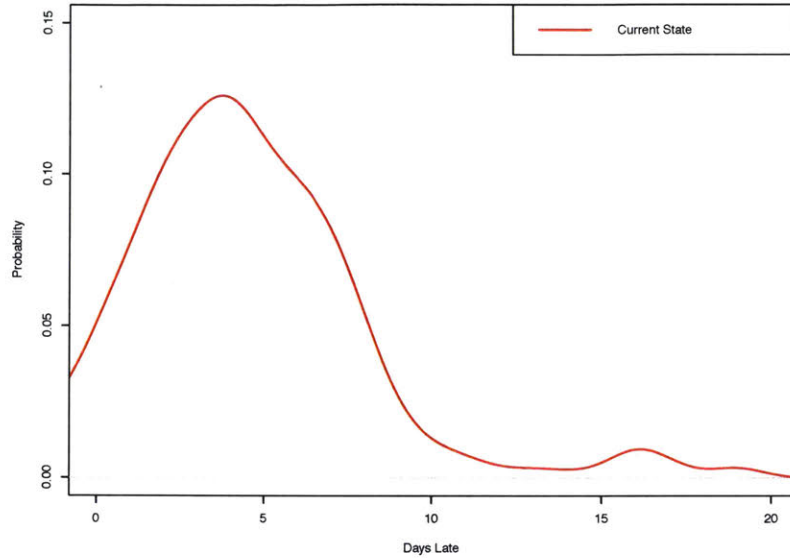


Figure 3-5: Closet completions, January 2016 to September 2017

Determining the Extent of Parts Shortages

After confirming the presence of late closet completions, the analysis turns to quantifying the extent of parts shortages and the impact of these shortages. The interview process indicates that parts shortages arise from two sources. The first source is parts that are intentionally not delivered because a part is out of stock. These are parts that are not available in the warehouse when a closet kit is built, which causes the warehouse to deliver the kit to the production floor with a known shortage. These shortages are known as SOS parts (the missing part is due to a source of supply issue). The second type of part shortage occurs when a part is not present in a kit due to a mistake in picking or an issue on the production floor (a part is lost, re-allocated, or broken). The production floor requests these parts from the warehouse through the Manufactured Parts Request (MPR) system, which requires non-value-added management effort.

With a knowledge of the ways in which a part shortage can occur, two density distributions are created using production system data. The first curve plots the probability of a closet order requiring parts that are not in stock (SOS parts), and the second curve plots the probability of a closet order requiring additional parts procurement through the MPR system. Figure 3-7 provides the results of these plots and indicates that a Program A closet

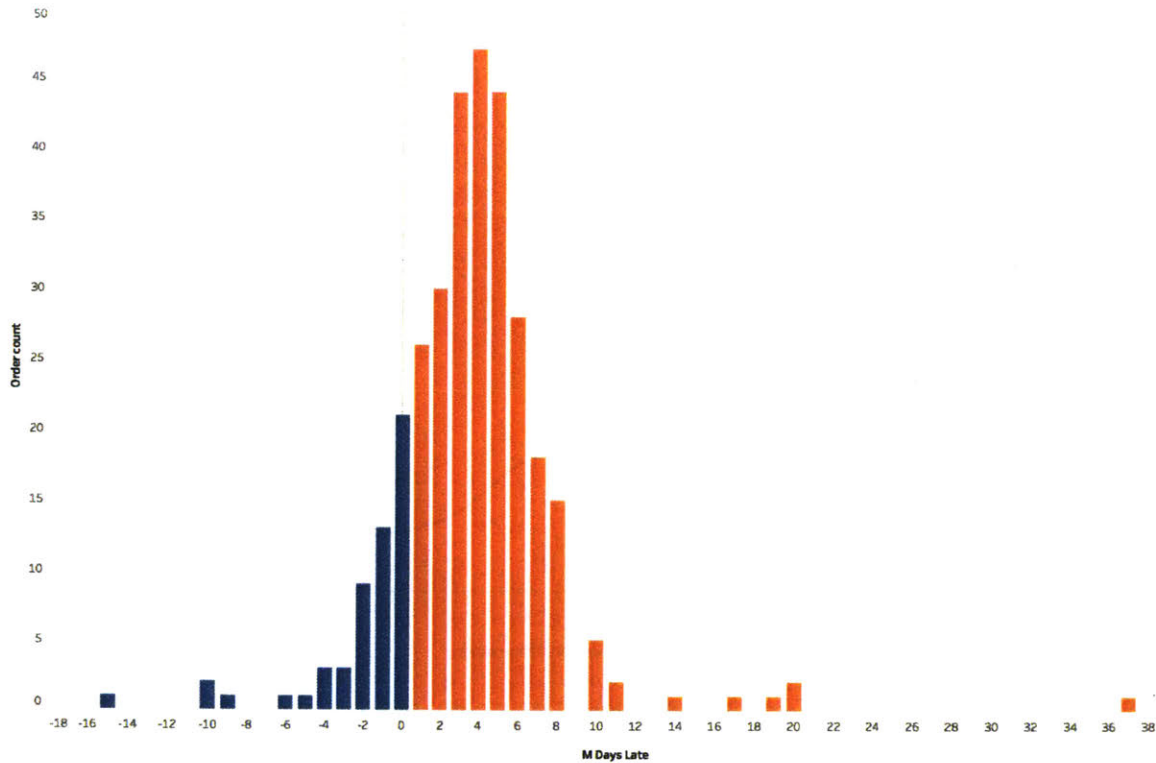


Figure 3-6: Closet completions for Program A aircraft, January 2016 to September 2017 *Early or on time completions are displayed in blue, while late completions are displayed in orange. The x axis indicates the number of days late or early a closet is completed, while the y axis indicates the number of occurrences for each x axis value*

order will likely be missing two parts due to stock out and require that an additional two parts be ordered through the MPR system.

Tabulating the results of this analysis indicates that 328 of the 470 (69.8%) of the closets assembled between January 2016 and September 2017 required at least one part after kit delivery, and the average closet kit requires two parts. Table 3.1 summarizes these findings. These results corroborate the anecdotal evidence found during the interview process.

Correlating Missing Parts to Late Completions

After verifying the existence of late closet deliveries and kits with missing parts, the final step in the current state analysis is to investigate whether missing parts contribute to late completions. The first step in this analysis is a side-by-side comparison of the late completion density distribution with the missing parts density distributions. This plot allows for a visual analysis of current state and whether a correlation exists. Figure 3-8 indicates that all

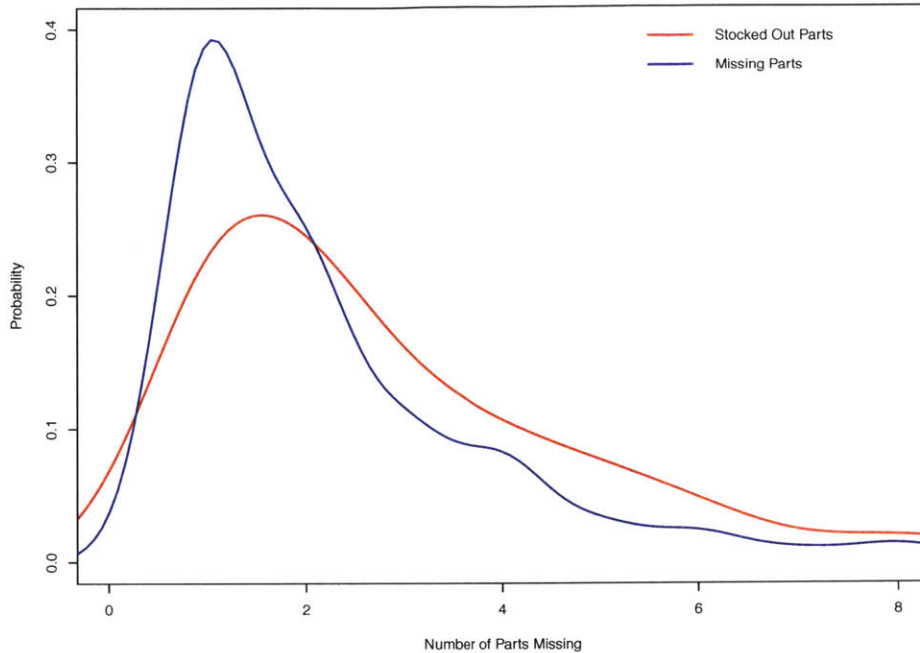


Figure 3-7: Monthly closet deliveries, January 2016 to September 2017

three factors have density distributions that peak away from the y-axis, indicating that late closet completions and missing parts are occurring simultaneously, which warrants additional investigation.

A linear regression provides insights into the extent to which incomplete kits impact late closet completions. Figure 3-9 contains the results of a linear regression that considers the number of days late a closet is completed versus the number of parts that are missing in a kit. This linear regression is produced by aggregating the number of times a kit is missing specific numbers of parts and finding the average number of days late the associated closet orders are completed. This regression indicates a positive correlation between missing parts and late completions, and that an increase in the number of parts missing from a kit leads to an increase in the number of days late a closet is completed. The regression also indicates that a closet with no missing parts will be 3.6 days late, which suggests the presence of other operational issues within the closet fabrication line. This finding appears consistent with the tabulated results presented in Table 3.1, which indicate that the fabrication line completes closets with no missing parts 4.4 days late. While these values do not match exactly, it is possible to conclude that there are underlying issues within the fabrication

Table 3.1: Missing parts analysis for the current state of operations

# Parts Missing	Avg Days Late	# Observations
0.00	4.40	142
1.00	3.86	111
2.00	3.26	73
3.00	4.78	58
4.00	4.32	25
5.00	3.96	25
6.00	4.50	16
7.00	5.25	8
8.00	5.20	5
9.00	6.43	7

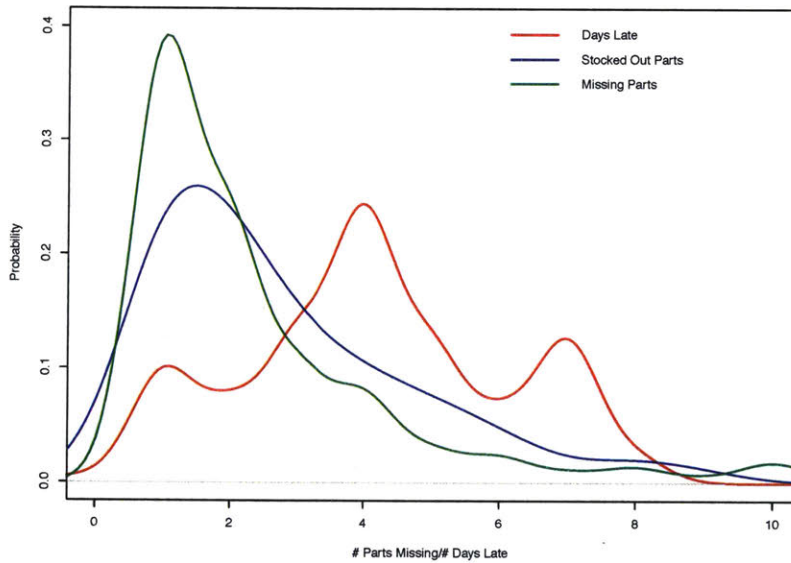


Figure 3-8: Density distributions for missing parts and days late for Program A aircraft

line that delay closet completions and parts shortages cause these delays to increase. In addition, the regression's R^2 value of 0.55 indicates that the relationship between missing parts and late completions is robust enough to warrant additional investigation and confirms the interview process's anecdotal findings.

3.5 Conclusions and Motivation for Future Research

After researching and quantifying the current state of the closet fabrication process, several facts become clear that influence the direction of this research. First, the evidence gathered

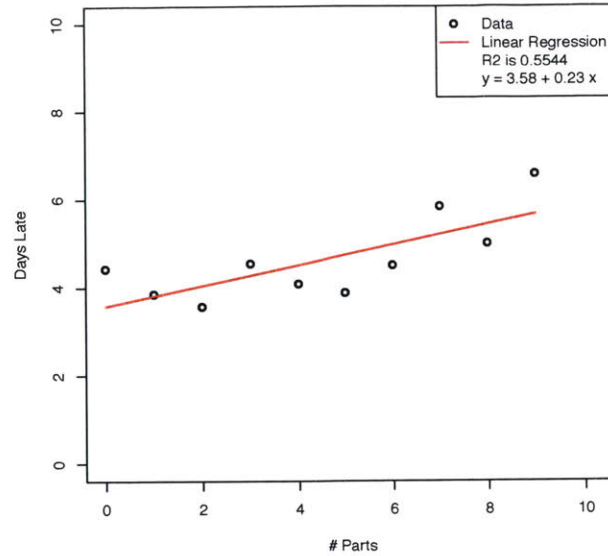


Figure 3-9: Linear regression of late completions vs missing parts, June to November 2017

during the interview process appears to be based on facts and can be corroborated with production system data. Second, there appears to be a correlation between incomplete kits and late closet deliveries. These findings indicate that the closet fabrication line has a problem regarding late completions, suffers from parts shortages, and that parts shortages influence late completions. These two issues are concrete problems and solving them has the potential to lead to meaningful improvements for the FF-A. For these reasons, this research shifts its focus to the issue of the delivery of incomplete kits to the FF-A closet fabrication line. The initial VML hypothesis remains unchanged, but narrows to focus on proving or disproving the hypothesis that the delivery of parts to a production cell improves when managers access and consume properly analyzed data.

Chapter 4

Benchmarking Best Practices

4.1 Kitting Background

Parts delivery is a common task across Boeing Commercial Airplanes. In many cases, Boeing delivers parts to mechanics in sets that contain all of the parts needed for a particular job or work package. These sets are known as kits, and the kits are assembled by a warehouse or outside supplier from a series of parts that are held in inventory. For a kit to be delivered to a mechanic with all of the necessary parts, the warehouse must know what kit is required, the BOM for the kit, and when the associated job will be started. If any of this information is not available, the warehouse struggles to provide the right parts, at the right time, to the right mechanic. In addition, the supply chain must support the kitting process by ensuring that the needed parts are available in the warehouse when needed. Finally, the warehouse must pick the correct parts, in the proper quantity, and add those parts to the correct kit. If the warehouse picks the wrong part, or the wrong number of parts, an incomplete or incorrect kit is delivered to the mechanic.

4.2 Challenge: Build Kits with Existing Systems

The kit assembly and delivery process comes with several challenges. First, the warehouse must have the correct parts on hand to put in the kit. Second, the warehouse must pick the correct parts in the correct quantity. Finally, the warehouse must deliver the kit to the right

mechanic at the right time. The FF-A warehouse faces these challenges, as does every kitting area within Boeing. The other challenge is improving the process while utilizing Boeing's current information technology systems, which is a key tenet of the VML concept.

4.3 Benchmarking Methodology

To identify the best kitting practices, observations and interviews are conducted at several fabrication and assembly sites in the Puget Sound area outside of the FF-A. These locations include Fabrication Facility B (FF-B), Fabrication Facility C (FF-C), and the Program B final assembly line. These interviews provide insights into how different organizations handle parts delivery, kit building, and work scheduling. All of these areas utilize the same ERP systems and must overcome similar challenges to complete their work. By consolidating all of the best practices found at these locations, this research intends to provide a series of recommendations to build complete and accurate kits.

4.4 Key Findings and Benchmarking Results

This research yields several key findings that are simple to implement and have the potential to improve operations within the FF-A and the closet fabrication line. These findings fit into three main categories: parts availability, scheduling and sequencing, and evaluation criteria.

4.4.1 Parts Availability

A key finding at the FF-C is that the kitting team does not begin to build a kit until all of the required parts are on hand. Prior to issuing the kit request to the warehouse pickers (pickers are the individuals who move throughout the warehouse and gather the needed parts from the warehouse shelves), a manager verifies that all of the required parts are on hand. If a part is not available, the warehouse does not begin picking the kit's parts. Once all of the required parts are available, the picking process begins. This method creates an initial barrier to incomplete kits and reduces the chance that a part is not available when the picker assembles the kit from inventory.

In the event that a part is not available once a kit begins the kitting process, the pickers at the FF-C pick as many parts as possible, and then place the kit in a special area near the warehouse's outbound shipping area. This special area, known as "jail," is only used for incomplete kits. If the spares center managers see a kit in "jail" that is a clear signal that there is a kit with a missing part that requires management attention. This system conveniently and clearly annotates incomplete kits and allows for the rapid resolution of these issues.

The FF-B also takes steps to ensure parts are available and to annotate clearly which parts are missing. If the FF-B kitting team builds a kit and discovers that a part is not available, the team places an orange placard on the front of the kit indicating what parts are missing. This orange placard is clearly visible and informs the mechanics of which parts are not available before work begins using that kit. While the FF-B does build kits prior to having all of the needed parts on hand, this facility indicates clearly what parts are missing and communicates the problem to the next node in the supply chain.

4.4.2 Scheduling and Sequencing

The FF-B does an excellent job of scheduling and sequencing work in a well communicated, clear order. This sequencing process allows the warehouse to know what parts are needed when and the order in which kits should be built. In the event that there are two kits that require the same part, and only one of those parts is available, a clear production sequence provides the warehouse with a priority order in which to fill the kits. This sequence allows the warehouse to provide the needed part to the first job in the production queue, thereby allowing the production floor to continue working and providing extra time to the supply chain to deliver another part.

The FF-B also uses a production sequence to time the deliveries of parts to the production floor. The production sequence for wire bundle assembly indicates the exact time a set of kits must be delivered to the production floor. The FF-B managers determine how much time the system requires between deliveries and use delivery times to ensure that parts are available when needed and prevent excess inventory from accumulating on the production floor. Both of these practices clearly communicate what parts are available and what parts

are needed when. This communication between the production floor and the warehouse is vital to the success of the FF-B's wire bundle assembly line.

The Program B production line also utilizes a scheduling system to deliver parts to the production floor. Kits arrive in two-hour intervals based on the work schedule generated by the program's industrial engineers. The industrial engineers group assembly work into two hour blocks and pass this information to the kitting building team. The kit building team is a third party that builds kits at a separate facility and delivers them to specific final assembly locations at the times designated by the industrial engineers. This system takes advantage of a deliberate production sequence that dictates what work will be completed in what order; however, the system does not have the ability to adjust to the production line's current state. Kits scheduled for delivery will arrive at the required time, regardless of whether the mechanics are ready for those parts. While the Program B industrial engineers have standard work packages to aid in the delivery of parts, the result is a system that cannot respond to the production system's current status. It is clear that sequencing work in a clear manner aids in the establishment of standard work; however, this system reinforces the notion that a supply chain that is not responsive to demand is not an ideal system.

4.4.3 Evaluation Incentives

The method used to evaluate a warehouse's performance impacts how well the warehouse builds kits. The FF-C delivers parts to customers (in this case airlines) whose aircraft are unable to fly for maintenance reasons. These customers require rapid assistance to repair their aircraft and return to revenue flight. As a result, the spares center assesses its performance by how quickly kits are built and by how accurate and complete the kits are. A kit that takes too long to build or does not have all of the needed parts is not satisfactory for the spares center.

However, the opposite is true for the FF-A warehouse. The evaluation criteria for the FF-A warehouse assesses performance based on kit delivery. The FF-A warehouse must deliver a kit one day prior to a job's scheduled start date. This criteria rewards kit delivery, but does not inspire kit completeness or accuracy. As a result, the FF-A warehouse prioritizes delivering kits on time, even if the kit is known to be missing parts. The result is the very

Table 4.1: Challenges and best practices found during benchmarking process

Facility	Challenge	Best Practice
FF-B	Sequencing parts for moving assembly line	Communicate schedule clearly and label incomplete kits
FF-C	Unknown demand for kits and rapid delivery required	Check inventory status before picking parts for a kit and isolate kits with missing items
Program B Final Assembly	Maintain takt time	Deliver parts in smaller kits designed for 2 hours of work

timely delivery of incomplete kits.

4.4.4 Successful Kitting Strategies in Different Environments

Each of these three locations operates in a unique environment that imposes different challenges. The FF-B assembles small, complex wire bundles quickly with the advantage of a known production schedule and significant visibility of future orders. These advantages allow the FF-B to develop a tightly controlled production sequence and prioritize parts in a logical manner. The FF-C faces the opposite challenge: the demand for spare parts is unknown, and a customer may require a kit at any time, anywhere in the world. While this challenge appears daunting, the FF-C developed standard work to limit the opportunities for a mistake to occur. While these challenges are different, the fact that both organizations find ways to succeed indicates that there are solutions to a wide variety of kitting problems within the confines of the current ERP systems. Table 4.1 provides a summary of the benchmarking process findings.

4.5 Conclusions

These findings provide valuable insights regarding the best practices for kitting and parts delivery at Boeing. They also provide guidance for how the VML concept can provide data to improve decision making in this area. The practice of verifying that all parts are on hand

before building a kit provides an excellent barrier to delivering an incomplete kit. Inventory data is readily available and easy to visualize, which makes an inventory on-hand element an attractive option for a VML tool. The communication required to transmit a production schedule or sequence is also an area that data analysis and visualization can improve. The FF-B excels at providing a paper-based schedule to multiple nodes in the supply chain and this process is a possible focus area for enhancement through data visualization. These two best practices provide guidance regarding how the VML concept can impact the delivery of parts to the production floor. In addition, the presence of kitting and parts delivery challenges across multiple facilities verifies that this problem is widespread, which makes a solution impactful across the organization.

Part II

Developing and Testing Solutions through Discrete Event Simulation

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 5

Improving Supply Chain Visibility through Discrete Event Simulation

5.1 Background of Supply Chain Visibility and Improved Communication

To solve the parts delivery problem, this research narrows its focus to providing managers visibility of three aspects of the supply chain. First, supply chain nodes outside the closet fabrication line require visibility of the production queue. Creating this visibility improves communication between supply chain nodes, thereby reducing confusion and allowing the supply chain to respond to changes or disruptions in a timely manner.

Second, managers throughout the supply chain require visibility of the warehouse's current inventory status. An understanding of inventory status allows managers to decide what closets to build based on parts availability. If all of the parts required to build a closet are available in the warehouse, that closet can be built without the delays associated with a missing part. It follows that a closet that does not have all of its required parts available in the warehouse may face delays during the assembly process and should not be started until all of the parts are available. This decision making process mirrors the best practices identified in Chapter 4.

Finally, a prioritized production queue reduces the number of days late closets are com-

pleted. This prioritization tool accounts for the historical time required to complete items in the production queue and the inventory status for each production order's BOM. By prioritizing the production queue in this manner, the warehouse can anticipate the production floor's requirements and provide parts punctually.

These three concepts form the core countermeasures to the obstacles identified during the root cause analysis and become the focus for the next phase of VML research. These concepts align with the research conducted by Nabil Adam and Julius Surkis regarding capacity planning in a job shop environment:

A system that will control and schedule jobs in a job shop environment requires three major components. Initially, a well-defined and properly updated data base consisting of routings, bills of material and status of orders has to be established. The second component should be a capacity planning or loading component that can provide an accurate forecast of loads for each time period for each work center and determine a realistic completion date for each new job entering the job shop. In addition to the data base and the capacity planning component, a detailed scheduling component would be necessary to establish priorities and sequence jobs at work centers. For the proper functioning of the three interrelated components a continuous flow of feedback data on the progress of jobs would also be required.[1]

While the closet fabrication line is not a job shop, the challenges present in the closet manufacturing process are similar to those faced in a job shop environment. The supply chain visibility concept detailed above follows Adam's and Surkis's recommendations.

This plan necessitates the development and testing of multiple methods to create the information managers require to improve operational performance. The testing process includes the development of metrics to assess changes to the closet fabrication line's performance and allows for the selection of the most effective methods for prioritizing the production queue. It is essential to test these methods in a digital environment prior to selecting a method for application on the production floor. As Earl LeGrande writes in his discussion of factory floor simulation at the Hughes Aircraft Company in 1963:

Simulation can be defined as the exploration of various courses of action in a decision-making situation, and anticipation of the consequences of each without actually trying out each course of action in the real world. If various alternatives are tried in the real world, this then becomes a process of trial and error and not simulation. Hence, in simulation, it is essential that alternative courses of action are explored before the decision is made.” [8].

This research accepts LeGrande’s advice and utilizes Discrete Event Simulation (DES) to implement LeGrande’s methodology.

5.2 Discrete Event Simulation Background

DES provides the ability to model the current state of the closet fabrication line, incorporate the uncertainty present in the production system, and assess the impact of changes made to the system in a digital environment. Unlike other modeling tools, DES’s ability to incorporate probabilistic events provides the analytical tool required to assess changes in a complex manufacturing environment. ProModel software provides the assets to develop the simulation. This software is commonly used at Boeing, and its selection allows future research projects to utilize this model.

To simulate the closet fabrication line’s operations, it is necessary to develop the needed inputs for the simulation. These inputs include locations, entities, arrival logic, and process logic. These four elements, known as LEAP, provide the information needed for the simulation to represent the variability present in the production system [4].

Locations are elements on the production floor where processes occur. In the case of the closet fabrication line, there are four main locations: the sweep and sand area, the kitting area, the tab and slot area, and the final assembly area. The next elements of the DES are known as entities. Entities are items that move through the simulation to replicate the flow of materials through the production system. In the case of the closet fabrication line, there are four entities: closet panels, closet parts, kits, and completed closets.

This simulation also includes mechanics, defined as entities, assigned to each location. The mechanics work a single eight hour shift per day, and the simulation utilizes two shifts.

The simulation assumes that overtime is not available. The number of mechanics providing overtime labor per week fluctuates based on production requirements, the number of mechanics willing to work on Saturday or Sunday, and the number of hours of overtime authorized for the closet fabrication line by the FF-A management. These factors are highly variable, making it very difficult to generate a model to predict overtime labor hours effectively. While this assumption simplifies the simulation by removing the need to estimate the overtime labor available during a week, it has the potential to lead to inconsistencies between the model and reality. Chapter 6 assesses this assumption's impact.

The arrival logic dictates when entities enter the simulated production system and specifies how many entities enter at once. In addition, the arrival logic specifies a time period during which entities arrive (such as only Monday through Friday), and the order in which entities move between locations in the simulation (using First In, First Out (FIFO) or Last In, First Out (LIFO), for example).

The final element in the DES is the process logic. Each location in the DES simulates a manufacturing process by utilizing one or more entities for a prescribed period of time. This time period may be fixed or variable, depending on the process. For example, a process logic may require an entity remain at a location for five minutes, or the logic may require that the entity remain at a location for a period of time defined by a probabilistic distribution (such as $N(5,1)$ minutes for example, where a normal distribution is defined by the mean process time of 5 minutes and a standard deviation of 1 minute). Defining the closet fabrication line process logic requires the analysis of production system data and the generation of probabilistic distributions.

5.3 The Probability Distribution Requirement

The central challenge in developing the DES is the development of the probability distributions that define the process logic throughout the simulation. Understanding and properly modeling these processes is essential to the simulation's accuracy. This challenge consists of several elements. First, the processes involved (and the associated start and end points) must be clearly defined. Next, the time required to complete each process must be observed,

and a probability distribution for each process's duration must be established.

5.4 Process Logic Development Methodology

Understanding and defining the processes present on the closet fabrication line is a simple task, while determining the time required to complete each task is more complex. Interviews and observations provide the establish the three locations and processes that occur on the closet fabrication line. Interviews also provide the basis for determining specific start and end points for each process. With this information, it is possible to determine the process durations.

The closet fabrication line's size and complexity make direct observation of the process durations difficult. The closets usually complete the tab and slot and final assembly processes on a single work bench, which makes the transition between stages difficult to detect. However, it is possible to determine which specific operations constitute the start and end of each process. With this knowledge, it is possible to identify the digital time stamps associated with the start and end of these operations. By assigning an operation to the start and end of each of the three processes, a start and end time for each process can be determined by accessing the production system data and extracting the time stamps of interest. A key assumption in this process is the simplification of the time stamp data to provide only the date an operation began or ended. Due to the cumbersome time stamp process, mechanics do not always submit digital stamps immediately upon completion of their work. As a result, this analysis considers only the date portion of the time stamps and uses days as the unit of time for duration analysis.

These data allow the creation of a series of probability distributions for each data set. From these distributions, the best fitting distribution becomes the defining distribution for the process logic. This methodology is executed using data from closets produced for all airplane programs; however, an analysis of the data indicates that the Program C, Program D, and Program E do not provide sufficiently large populations to develop effective distributions. These programs also build closets at a low rate, which limits the utility of implementing changes to these processes. After assessing these issues and discussing them

with the closet fabrication line management team, it is decided to limit this simulation to Program A and Program B closets.

5.5 Data Analysis and Distribution Fitting

This method is executed for the sweep and sand, tab and slot, final assembly processes for the closets produced for the Program A and Program B aircraft. To generate this data set, the closets built over a 120 day period are considered. Closets built between June 1, 2017 and August 31, 2017 comprise the data set, which yields 67 closets for Program A aircraft and 33 closets for Program B aircraft. A 120 day period is selected based on discussions with the closet fabrication line’s manager. Due to process changes associated with continuous improvement initiatives, the managers recommend that only closets built within the last 120 days be considered in the simulation, as closets fabricated outside this time period may not represent the production line’s current state.

After completing this analysis, normal, Poisson, exponential, and negative binomial distributions are fitted to the resulting data utilizing a distribution fitting package in R. This package modifies the descriptive parameters for each distribution until a best fit is achieved. The results are then plotted with a histogram of the production system data to assess which probability distribution best represents each process. Figure 5-1 provides an example of the output generated from this process, while Table 5.1 provides the key parameters determined for each of the plotted distributions. The remainder of the plots and key parameter tables are available in Appendix A.

Table 5.1: Distribution parameters for the Program A final assembly

Distribution	Parameter	Value
Poisson	Rate	3.88
Normal	Mean	3.88
Normal	Std Dev	4.27
Exponential	Rate	1.34
Negative Binomial	Size	3.88
Negative Binomial	Mean	0.26

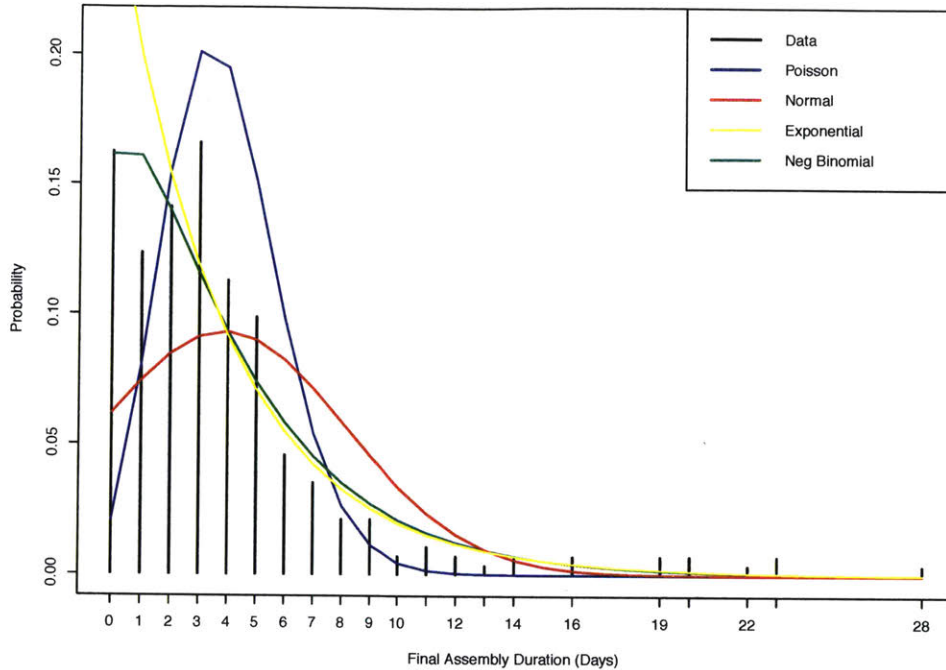


Figure 5-1: Comparison of probability distribution fits for Program A closet final assembly process

5.6 Results and Distribution Selection

After plotting the data and distributions, it is clear that certain distributions fit the data better than others. The best fitting distribution is generally the negative binomial distribution, followed by the Poisson distribution. In the interest of maintaining a model that can be utilized for future research, the Poisson distribution is chosen. The ProModel software supports the use of the Poisson distribution, but not the negative binomial distribution. Given the utility of creating a sustainable simulation and the limited improvement generated by using the negative binomial distribution, the Poisson distribution becomes the clear choice for this research.

5.7 Conclusions

While these distributions do not fit the data perfectly, they provide a starting point to generate an initial model and test whether the model's results deviate from actual results in a statistically significant manner. The next phase of this research is the validation of the

simulation using historical production system results.

Chapter 6

Validation of the Discrete Event Simulation

6.1 Validation Requirement and Background

The next task is the validation of the model to ensure that it generates results that properly reflect the closet fabrication line's performance. This validation requires the comparison of two performance metrics. The first metric is the time required to produce a closet, referred to as the build duration. The build duration is the elapsed time from the start of the closet fabrication process to the end. The second metric is whether the production line completes a closet on time. This on time performance (referred to as days late) is measured by the number of days late (or early) a closet is completed when compared to its schedule completion date. Comparing the simulation's results to the closet fabrication line's actual performance indicates how well the simulation replicates reality and provides insights regarding the proper method to analyze and compare the results of changes made to the production system.

6.2 Validation Challenges

There are several challenges associated with validating the simulation. First, the validation requires a data set to serve as a control group. Second, there must be a means to test whether the simulated results of the control group input are significantly different from the results

that occurred in actuality. Obtaining the control group data requires the identification of a statistically significant sample of previously built closets. This data sample includes the build duration for each closet, each closet's scheduled completion date, and each closet's actual completion date. In addition, this control group must comprise closets from both Program A and Program B.

Next, the simulation must fabricate these closet orders in the digital environment. This process generates the build duration and days late data needed to compare the simulation's performance with the performance of the physical production floor. This comparison requires the use of a statistical test to determine whether the difference in the simulated and actual results are statistically significant. If the difference between the two results are not statistically significant, the simulation results are valid and the DES can be used to assess the impact of changes made to the closet fabrication line's operations. If a statistically significant difference is present, the simulation must be improved and/or a new method to assess the impact of production system changes must be developed.

6.3 Simulation Validation Methodology

The validation methodology utilizes historical production system data to generate a control group data set. The simulation then uses this control group data to create simulated outputs that are compared to the results generated by the actual fabrication line. These results are compared with a two-sided, paired t-test to test for a statistically significant difference in the means of the actual and simulated results. The control group data are taken from a series of closets produced during a 120 days period ranging from June to August 2017. A key component of the control group data is that the sample size must be large enough to ensure that the simulation process reaches a state of statistical equilibrium. In their study of job shop simulation, C. T. Baker and B. P. Dzielinski explain this challenge:

Two points are considered in taking a sample of data from the model. First, for these tests we wish to be assured that the model is in a statistically stable state. This is necessary since at the start of the simulation run the shop is completely idle. When the first unit load is released, work on it starts immediately. However,

when the second unit load is released, it cannot be started as promptly as the first load, since the shop is still working on the first load. This kind of delay also occurs for the third, fourth, and all subsequent unit loads. Eventually however, these delays stabilize, at least in a statistical sense. A statistical analysis of the average of the jobs' total manufacturing times showed that after twenty unit loads had been released to the system, a statistical equilibrium was established.[3]

Utilizing a large control group (in this case, 100 closet orders) allows the simulation to achieve the statistical equilibrium Baker and Dzielinski describe. The 100 closets in the control group are loaded into the simulation's arrival logic and built in the digital production environment. As the simulation processes the closet orders through the digital production environment, the simulation generates a series of time stamps that indicate when each closet started and ended each of the three fabrication processes. Finding the difference between a closet order's start and end time stamps provides the build duration data for that closet order. Comparing a closet's final time stamp to its scheduled completion date indicates how many days early or late the simulation completed the closet. Comparing the mean values of the actual and simulated results is accomplished using a two-sided, paired t-test. This statistical test is a hypothesis test that determines whether to reject the null hypothesis. In this case, the null hypothesis states that the difference in the mean values between the simulated and actual results is zero:

$$h_0 : \mu_{actual} - \mu_{simulated} = 0 \tag{6.1}$$

The alternate hypothesis states that the difference in mean values is not equal to zero:

$$h_1 : \mu_{actual} - \mu_{simulated} \neq 0 \tag{6.2}$$

The two-sided, paired t-test utilizes a 95% confidence interval. If the test fails to reject the null hypothesis, then it is possible to be 95% confident that the simulated and actual mean values have no difference in their values. This outcome validates the simulation. If the statistical test rejects the null hypothesis, then the simulated and actual mean values are different, which implies that the simulation does not model the physical production line

correctly.

6.4 Data Utilized for Validation

The data utilized for the validation process are the closet orders that comprise the control group. This information provides actual start and end times from the actual production process. These data provide a statistically significant sample size that represents a standard workload for the closet fabrication line over a 120 day period. The closet orders contained within this data set are entered into the simulation in the order in which they were built on the production floor to replicate the actions taken by the production floor managers and team leads. Executing the simulation with this data set and conducting the two-sided, paired t-test on the results generated the following outputs. The build duration results and days late for closet completions are depicted as density distributions in Figures 6-1 and 6-2, respectively.

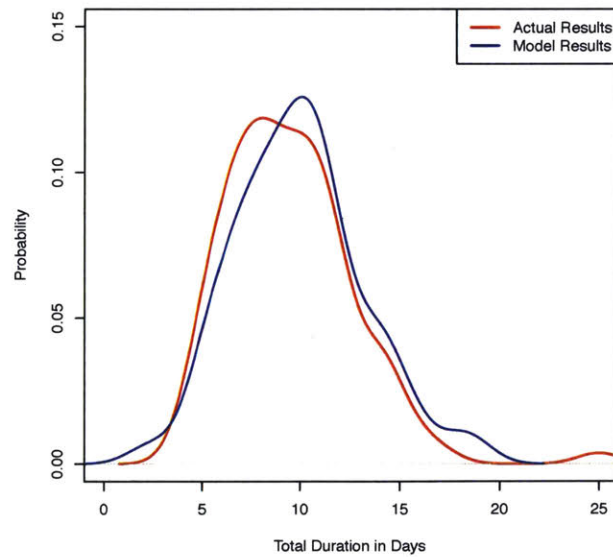


Figure 6-1: Comparison of actual and model build duration results

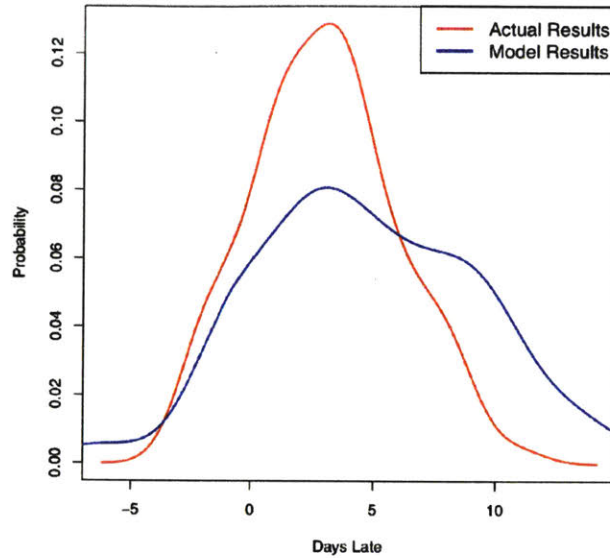


Figure 6-2: Comparison of actual and model late completion results

6.5 Results of the Validation Process

A visual examination of the density distributions provides the initial results of the validation process, which are then reinforced by the results of the hypothesis test. The density distributions indicate that the simulation produces results that are accurate for the closet build durations, but are less accurate with respect to the number of days late for closet completions.

In Figure 6-1, the density curves match closely, indicating that the simulation models reality well. However, the density curves are noticeably different in Figure 6-2, indicating that the simulation fails to provide an accurate representation of how many days behind (or ahead) of schedule a closet will be completed.

The hypothesis test results confirm these observations. The t-test for the closet build duration yields a p-value of 0.70, which is far greater than the value of 0.05 used to generate the 95% confidence interval. In addition, the absolute value of the test t-statistic (-0.38) is less than the critical t value of 1.98, and the confidence interval for the mean difference includes 0 (the confidence interval ranges from -1.18 to 0.80). These three findings indicate that there is not statistically significant evidence to reject the null hypothesis. Because this test fails to reject the null hypothesis, the difference in means between the simulated and

actual closet build durations is taken to be 0, with a 95% confidence level. These results validate the simulation's ability to model closet build durations. Table 6.1 summarizes the results of this hypothesis test.

Table 6.1: Results of t-test for build duration results, actual vs simulated

Estimate	t-Stat	p Value	Conf Int Low	Conf Int High	t Crit
-0.19	-0.38	0.70	-1.18	0.80	1.98

However, the model does not perform as well regarding the number of days behind schedule a closet is completed. The hypothesis test reports a low p-value of 0.02, which is less than the value of 0.05 utilized to generate the 95% confidence level. In addition, the confidence interval for the difference in mean values does not include 0, and the absolute value of the t test statistic (-3.71) exceeds the t critical value of 1.98. Table 6.2 summarizes the results of this hypothesis test. Given these results, the null hypothesis must be rejected, which indicates that the difference in mean values between the number of days late for a closet order generated by the simulation is statistically different than actuality. As a result, the simulation cannot be validated for this metric.

Table 6.2: Results of t-test for late completion results, actual vs simulated

Estimate	t-Stat	p Value	Conf Int Low	Conf Int High	t Crit Value
-1.72	-3.71	0.02	-2.64	-0.80	1.98

6.6 Conclusions

Based on the results of these hypothesis tests, the simulation performs well regarding the time required to build a closet, but does not perform well when predicting how many days early or late a closet order is completed. These results are not surprising. The time required to complete each phase of the closet fabrication process has few opportunities to fluctuate. Once a mechanic begins work on a particular phase of the closet fabrication process, pending interruptions due to outside factors, the closet will be completed in a predictable duration. The time required to assemble parts, apply epoxy, and allow the epoxy to cure is well known.

As a result, the data utilized to generate the process logic in the simulation represent reality accurately.

However, the process for ensuring the production floor delivers closets to the customer (aircraft final assembly) is more difficult to model. Observations on the production floor indicate that as managers realize that certain closets will not be completed on schedule, they begin to shift the order in which mechanics work on closet orders. This management by exception allows the production floor to finish closets that are deemed to be behind schedule and critical to the customer. These decisions are made by managers, and are difficult to simulate in a digital environment. As a result, the simulation builds closet orders in the order they were generated, and does not take into account any external factors that would lead to a change in work priorities. This difference in the way in which the closet orders are prioritized impacts the number of days behind schedule for a closet order in the simulation and prevents the simulation from producing results that are statistically similar to the production floor's actual results.

Given these findings, it is reasonable to compare changes made in the simulation to the actual results generated by the production floor. A change made in the simulated environment can be compared against actual results to assess whether that change leads to a positive improvement for the fabrication line. This is not the case with the late completion metric. In this case, the simulation does not perform well enough for a direct comparison between simulated and actual results. Therefore, it is necessary only to compare simulated results when evaluating whether a change to the production system yielded positive or negative changes to the line's days late performance.

In light of these findings, this analysis executes data comparison in a distinct manner. With regard to the build duration metric, results are compared against the baseline simulation created with the control group data and with the actual results associated with the control group closet orders. For the days behind schedule metric, the results of a change are compared only to the simulated results associated with the control group data. This approach provides a logical method to evaluate the impact of a change given the strengths and weaknesses of the discrete event simulation.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 7

Testing Prioritization Methods using the Discrete Event Simulation

7.1 Background

While the initial VML prototype provides a digital representation of the production floor's current status, it is necessary to add additional tools to provide managers with information regarding inventory and production queue prioritization. This chapter addresses the development and evaluation of prioritization tools with the intent of minimizing the average number of days late the production line completes an order.

One tool to improve manufacturing performance is a prioritization system that informs the warehouse and fabrication floor managers of the production sequence that minimizes late order completions. This prioritization tool rank orders the production queue in a manner that considers historical build times, the time available to a complete a build, and leverages one of Boeing's greatest strengths: the presence of a known production schedule. Given the lead times required to manufacture a commercial airplane, the production queue is known in advance, and airline customer demand is essentially deterministic. Baker cites scheduling as an opportunity to improve operations, and these improvements are the goal of the prioritized production queue:

"For factories which are substantially deterministic, scheduling can provide a

number of advantages over dispatching. The scheduling system can be used to reduce randomness in the factory, thus reducing inventories and lead-times...Scheduling can be used to search for globally (across resources and across time) optimal or close-to optimal results” [2].

Currently, the closet fabrication line industrial engineer uses a heuristic to sequence closet orders in the production queue. This system reduces visibility of the production queue to the closet fabrication line, and does not share the information with other parts of the supply chain. Given that the airplane production schedule is set far in advance, it is logical to extend this knowledge to additional nodes in the supply chain and allow each node to schedule its work to achieve a common goal: meeting the production schedule.

While Baker’s approach to scheduling considers the factory as a whole, this prioritization tool influences only the scheduling of work on one fabrication line. In addition, the prioritization only impacts the decisions made immediately before the start of the manufacturing process. Boeing’s ERP and supply chain systems require significant lead times to procure, receive, and distribute the parts needed to build an airplane. In the case of this prioritization tool, the goal is to advise managers which closet order to introduce onto the manufacturing floor next, while providing the warehouse with visibility of what closet orders require kits in the near future. These decisions occur one to two days prior to the start of manufacturing, well after the supply chain analysts and industrial engineers have coordinated the flow of materials into the greater production system.

In addition, the prioritization tool allows the warehouse to allocate parts to kits properly. In a situation where there is one part in stock and two kits require this part, the warehouse must assign the part to the most urgent closet order kit. Without access to a prioritized production queue, this allocation decision becomes very challenging. While the prioritization tool does not eliminate the presence of a stocked out part, it does provide an opportunity to reduce the impact of the unavailable part on the production floor’s performance.

7.2 Selecting the Proper Prioritization Method

Developing and selecting the correct prioritization method requires the use of DES. This problem has two components. First, methods and options for prioritizing the production queue must be researched and developed. Second, these options must be tested to identify which of the methods is most effective (and to ensure that implementing a prioritized production queue will not lead to a degradation in system performance).

7.3 Methodology for Comparing and Evaluating Prioritization Methods

To overcome these challenges, the problem solving process researches other manufacturing environments that require scheduling and prioritization to reduce late completions, and identifies prioritization methods for consideration and evaluation. Next, these methods are tested by implementing them in the DES. LeGrande writes that a key reason for developing a factory simulation is "to evaluate the effects of various dispatch rules. Under a given set of conditions, various dispatch rules can be used in simulation to determine the effect of each on order completion, inventory costs, and other criteria. Hence, for a given set of conditions management can choose the priority rule which best meets its objectives." [8] In the case of the closet fabrication line, management wishes to improve timely closet order completions.

Changing the order in which the simulation starts closet orders and passes them through the system generates data that provide insights into how best to introduce and transfer work on the production floor. Once the prioritization methods are selected, implemented in the simulation, and the simulated results have been generated, it is necessary to test for statistically significant changes in the production system's performance. This analysis utilizes a hypothesis test similar to the one used in Chapter 6. These results provide a quantitative analysis of which prioritization tools yield a statistically significant change in the performance.

7.4 Comparison and Evaluation Data

7.4.1 Prioritization Methods and Techniques

This research focuses on the methods listed in Panwalkar's overview of scheduling rules, and specifically those that focus on due dates [9]. Several rules apply to this desired outcome, and the rules rely on an order's due date, the current date, and the number of operations required to complete the order to develop a prioritized list of work. Panwalkar's survey leads to research conducted at the Hughes Aircraft Company by Michael H. Bulkin, John L. Colley, and Harry W. Steinhoff. At Hughes, these researchers encountered a job shop environment that struggled to complete its work on schedule, and decided to test a computerized production schedule to overcome these challenges. This research team discovered that "schedule performance in job shops with fixed completion schedules was highest when the Minimum Slack-Time Per Operation Rule was used" [6]. This minimum slack time per operation rule considers the amount of time available to complete an order, the time usually required to complete the order, and the number of operations required.

$$\text{Slack Time per Operation} = \frac{RT - RPT}{NOR} \quad (7.1)$$

where RT is the required due date, RPT is the remaining time to completion, and NOR is the number of operations remaining. The time values have units of days. This equation produces a score that allows for the prioritization of work. The lower an order's score, the higher its priority. With this information, orders with the lowest slack time score proceed through each step of the fabrication process first. This system requires that slack time scores receive continual updates, which necessitates the use of a digital system to track the progress of orders through the fabrication process. Figure 7-1 depicts the slack time available for a hypothetical closet order.

In addition to the slack time per operation method, Panwalkar's survey also suggests that FIFO is an effective method for minimizing late completions. In this method, the first order to enter the production floor is the order with the lowest priority score. Once the order completes the first process in the production sequence, the order passes through the

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	2	3	4	5	6	7
	Current date	Slack time				
8	9	10	11	12	13	14
	Build duration					
15	16	17	18	19	20	21
					Completion Date	
	Build duration					
22	23	24	25	26	27	28

Figure 7-1: Visual example of slack time determination

The slack time is the time remaining that is not utilized by the expected build duration.

remaining steps in FIFO order. This method decreases the administrative burden generated by the slack time system in which priority scores are dynamic and constantly update as orders progress through the factory.

These findings lead to two prioritization methods. The first assigns orders a priority score using the slack time per operation method. This score determines the sequence in which closet orders enter the production system. In addition, this score dictates the order in which closets flow between processes on the production floor. Under this system, if two closet orders are completed at the same time at the sweep and sand process, the closet with a lower priority score (a lower score indicates a higher priority) would move to the tab and slot process first. This system requires that a priority score be maintained for each order, which may create an administrative burden for managers and team leads.

The second methods utilizes both the slack time per operation method and FIFO to prioritize orders on the production floor. Closet orders enter the production system according to their slack time per operation score (starting with the lowest scores), and progress through the production system according to FIFO. This method allows work to enter the production system according to its priority score and allows managers and mechanics to pass work through the system using the FIFO method. This system appears useful as it does not

require managers, team leads, and mechanics to track and update order priority scores during the production process.

7.4.2 Testing the Prioritization Methods through Simulation

To test the prioritization methods, the DES builds the control group closets using the slack time per operation method (slack method) and the slack time per operation method with FIFO method (slack/FIFO method). The control group data referenced in Chapter 5 serve as the input data for this testing process. Each closet order in the control group receives a slack method priority score based on its scheduled completion date and mean historical build time. The simulation runs twice, once using the slack method, and once using the slack/FIFO method. Simulation results are collected from each simulation for analysis. In addition to these two priority methods, the simulation is also executed using a random order to build the closets. The results of this random execution provide a baseline performance level to indicate whether the prioritization tools are more useful than a purely random execution of work. If not, the initial problem solving approach may not be valid.

7.5 Results

Simulating the closet fabrication line's operations using these prioritization tools identifies which method is most effective. This analysis continues to use the build duration and days late metrics defined previously. Simulated results are collected for the current prioritization method in use on the production floor, the slack method, the slack/FIFO method, and the random method.

With this information, a two-sided t test evaluates the hypothesis that there is no difference in the mean values of the two metrics for these prioritization methods. For each prioritization method, the null hypothesis states that the difference between the actual mean build duration for a closet and the simulated build duration for a closet (using the prioritization technique) is zero:

$$h_0 : \mu_{actual} - \mu_{simulated} = 0 \tag{7.2}$$

The alternate hypothesis states that the difference in mean values is not equal to zero:

$$h_1 : \mu_{actual} - \mu_{simulated} \neq 0 \tag{7.3}$$

If the null hypothesis is not rejected, then there is a 95% confidence level that the prioritization method did not produce a statistically significant change to the mean build duration for a closet order. This process is repeated for the mean number of days late a closet is completed to assess the impact the prioritization methods have on late completions.

Figure 7-2 provides the density distributions for the closet build durations generated using the two prioritization methods. The results of the hypothesis tests are reported in Table 7.1.

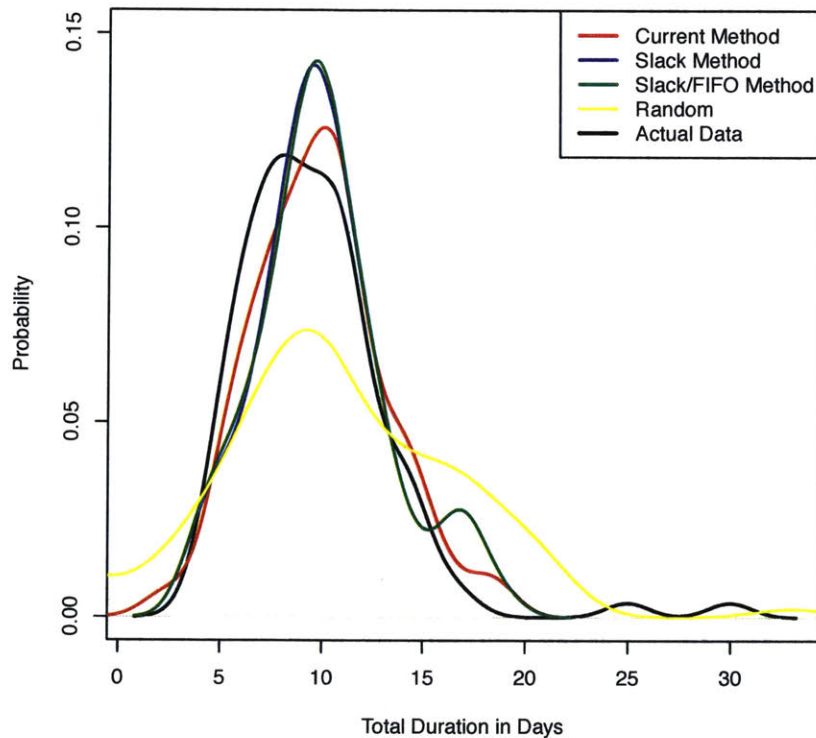


Figure 7-2: Comparison of probability distributions for build durations, all prioritization methods

In Table 7.1, the "Estimate" column indicates the estimated difference in build duration for each prioritization method when compared with the current method (negative values imply the tested method will lead to a shorter build duration). The t stat, p Value, and confidence

Table 7.1: Hypothesis test results for build duration

Estimate	t-Stat	p Value	Conf Low	Conf High	t Crit	Scenario
-0.19	-0.38	0.70	-1.18	0.80	1.98	Actual vs. Model
-0.47	-0.68	0.50	-1.84	0.90	1.98	Actual vs Random
-0.39	-0.83	0.41	-1.33	0.55	1.98	Actual vs Slack
-0.39	-0.82	0.41	-1.33	0.55	1.98	Actual vs Slack/FIFO

interval columns report the results of the statistical test. These results indicate that there is no statistically significant difference in build durations between the prioritization methods.

While the prioritization methods do not improve the time required to build a closet, they do impact late closet completions. Figure 7-3 and Table 7.2 report the results of the hypothesis test for the mean number of days late the control group closets were completed using the prioritization methods.

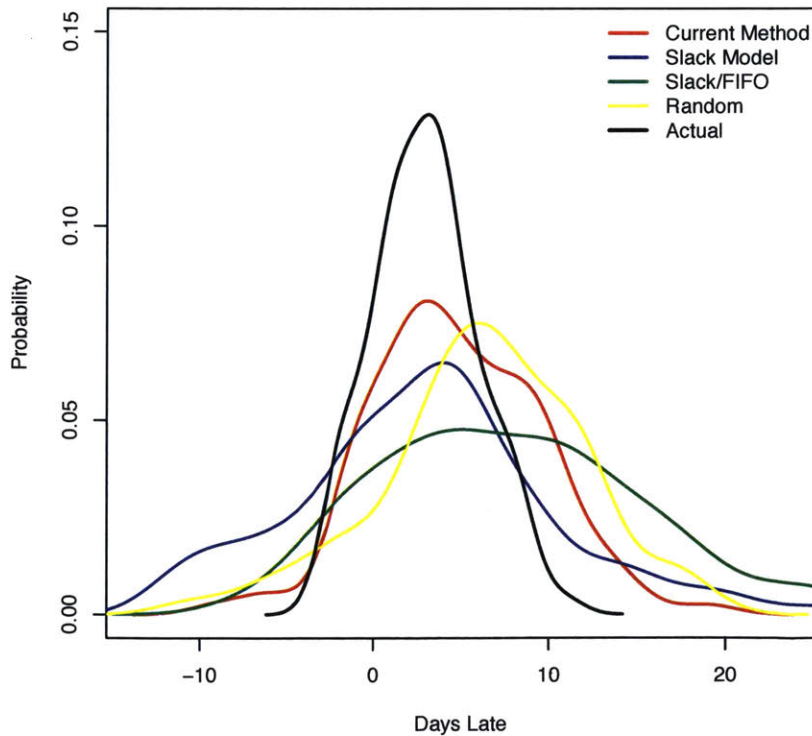


Figure 7-3: Comparison of probability distributions for late completion days, all prioritization methods

Visually, the slack model appears to provide a greater density of closets completed on time or early. The results of the hypothesis test indicate that the difference in the mean number of

Table 7.2: Hypothesis test results for late completion days

Estimate	t-Stat	p Value	Conf Low	Conf High	t Crit	Scenario
1.78	1.80	0.07	-0.18	3.74	1.98	Model vs Slack
-2.93	-4.01	0.00	-4.38	-1.48	1.98	Model vs Slack/FIFO
-1.48	-2.40	0.02	-2.70	-0.26	1.98	Model vs Random

days late is also statistically significant. The hypothesis test indicates a p value greater than 0.05 ($p = 0.07$), which provides reason to reject the null hypothesis. The absolute value of the test t statistic is also less than the critical t value. Given these findings, it appears that there is a small, yet statistically significant difference in the number of days late a closet is completed when using the slack prioritization method. As discussed in Chapter 6, the analysis of the number of days late closets are completed requires that simulation results be compared. Comparing simulated results with other simulated results allows for a sound data analysis due to the differences between the simulated and actual results discussed in Chapter 6.

7.6 Conclusions

These results generate several conclusions. First, the prioritization method does not appear to have any impact on the time required to build a closet. These results are logical given that the work performed at each stage of the fabrication process does not take more or less time based on the sequencing of the closet orders. Each operation in the closet fabrication process takes the same amount of time, regardless of which closet is built first.

This result is not true for the number of days late the closets are completed. When higher priority closets are built first, the average number of days late the closets are completed decreases in a statistically significant manner. This outcome is logical when considering the allocation of available time and resources within a production line. If one considers a production queue, each order in the queue must wait until the orders ahead of it are complete. By sequencing orders in a manner that places orders with earlier completion times at the front of the queue, the overall tardiness of the system will decrease. The slack time formula accomplishes this task and aligns orders in a fashion that reduces opportunity for an order

to fall behind schedule.

This outcome aligns with previous research conducted by Donald Carroll during his PhD research at the MIT Sloan School of Management. Carroll's study of sequencing heuristics found that the slack time prioritization rules perform well in several studies by minimizing the variance present in a production system: "sequencing in order of minimum slack (due date less remaining processing time) would be likely to provide lower variance...In effect, the rule would consider total processing times upon release of orders rather than after the order had incurred considerable delay. Another favorite rule has been minimum slack per remaining operation (SLROP)...Rowe found it best, Gere found it superior in his dynamic studies, and Conway's RAND studies confirmed this." [7]. Given this finding, the slack time per operation method is chosen to prioritize work.

Chapter 8

Testing the Impact of Improved Kit Delivery on Production System Performance

8.1 Simulating Improved Kit Delivery

After prioritizing the production queue, this research assesses the impact of delivering more complete kits to the production floor. Currently, 69% of the kits received by the closet fabrication line are missing parts¹. It is hypothesized that delivering a greater percentage of complete kits leads to improved manufacturing performance. The DES evaluates this hypothesis and provides justification for future research in a live production environment.

8.2 Simulation Challenges

The key challenge to evaluating the performance improvement generated by improved kit delivery is the method for simulating a change in the percent of kits that arrive complete. This analysis requires a method to simulate the use of a VML tool that improves decision making, thereby increasing the percent of complete kits that arrive on the production floor.

¹This analysis is based on the 472 closets built from June 1, 2017 to November 28, 2017. Of these 472 closet orders, 145 were built with kits that had zero missing parts. See Table 11.5 for additional details.

As the managers' decision making improves with better information availability, it is assumed that the percent of complete kits delivered to the production floor increases.

8.3 Improved Kit Delivery Evaluation Methodology

The methodology for evaluating the impact of improved kit delivery has three elements. First, a probability distribution models the number of parts missing per closet. Next, a linear regression determines the amount of time added to a closet's build duration by a missing part. Finally, this additional build time incurred due to missing parts is removed from the simulation's process logic to reflect the delivery of more complete kits.

To develop a probability distribution that models the number of parts missing from a closet order, the methodology used to develop the simulation process logic is applied to the missing parts data referenced in Chapter 3. This probability distribution assigns a number of missing parts to each closet in the control group data set. The number of missing parts assigned to a closet order is stored in the control group data and serves as an additional simulation input.

The next step is the determination of the amount of time added to a closet's build duration when a part (or multiple parts) is missing. Using Program A and Program B closets fabricated from June 1, 2017 to November 1, 2017, a linear regression relates the additional time required to build a closet to the number of parts missing from a closet order (see Figure 8-1).

This linear regression provides a baseline number of days late closet orders are completed (the y-intercept in the linear equation), and the additional delay generated by each missing part (the coefficient of the independent variable). The independent variable's coefficient represents the additional time required to build a closet when a part is not available. The additional time required increases linearly as more parts are missing from a closet kit. This methodology assumes that any delay beyond the baseline value determined by the y-intercept is entirely due to a parts shortage.

The final step in this methodology is the reduction in the time required to build a closet as the percent of complete kits delivered to the production floor increases. This

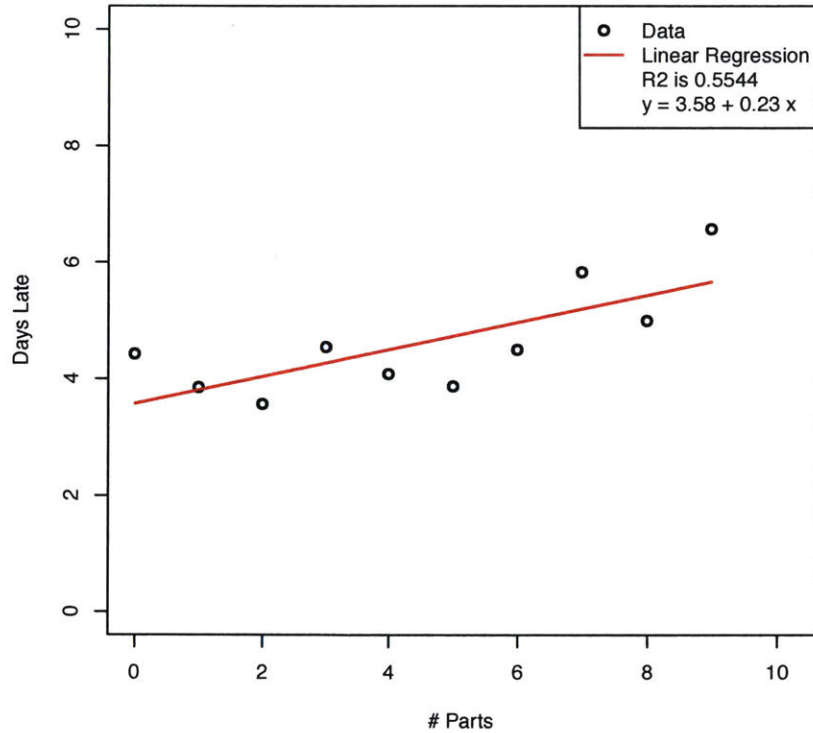


Figure 8-1: Linear regression of late completions vs missing parts, June to November 2017

methodology makes an initial assumption that 50% of the kits delivered to the production floor are currently complete (in this context, a complete kit arrives with all of its required parts). This assumption accounts for the fact that some parts requests generated to fulfill parts shortages on closet orders are the result of parts that are broken or lost once a kit arrives on the production floor. This assumption makes a conservative estimate of the incomplete kit delivery issue to avoid overestimating the impact of improvement to the delivery system. As the percent of complete kits increases, the time required to fabricate a closet is reduced by the same percentage. For example, if the number of complete kits delivered increases by 10%, and the closet kit was missing one part, the simulated build time reduces by 10% of the missing part penalty determined by the linear regression.

8.4 Distribution and Regression Data Inputs

This process generates two data inputs that drive the adaptation of the DES to model the impact of improved parts delivery. The first input is the probability distribution that assigns

a number of missing parts to a closet order. Figure 8-2 depicts the results of fitting four probability distributions to the missing parts data collected for Program A and Program B closets built from June 1, 2017 to November 1, 2017. This data includes both parts that were out of stock at the FF-A warehouse and parts the production floor ordered through the MPR process.

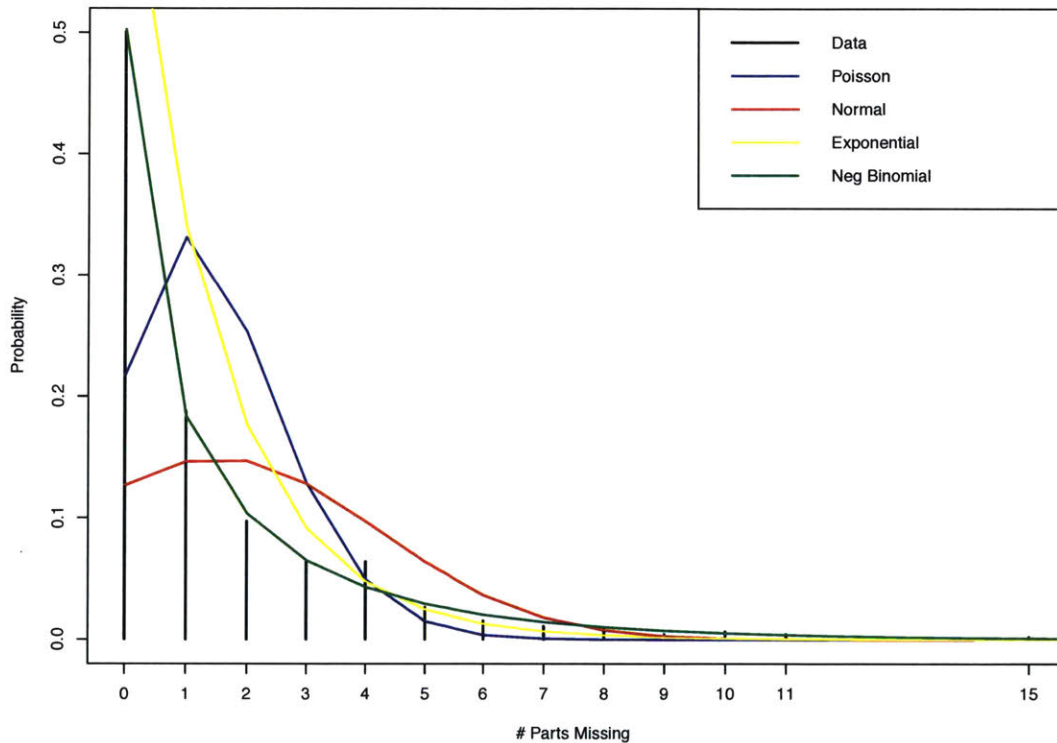


Figure 8-2: Probability distribution fitting for parts missing per closet

This distribution fitting process indicates that the negative binomial distribution provides the best fit to the data; however, the Poisson distribution is utilized to model the number of parts missing in a kit for the same reasons discussed in Chapter 5.

The next input is the amount of time the absence of a part adds to a closet’s build time, which the linear regression results provide. This process yields the following linear equation that relates closet completion delays (annotated as days late on the graph) to the number of parts missing from a kit at the start of the fabrication process.

$$y = 3.58 + 0.23x \tag{8.1}$$

In this equation, y is the number of days late a closet is completed (the build duration) and x is the number of parts missing from the closet's kit. Equation 8.1 and the associated plot depicted in Figure 8-1 indicate that a closet with no missing parts will be completed 3.58 days late, and each additional missing parts adds an additional 0.23 days to the delay. This procedure allows for an analysis of how much time in a closet order's build duration is actual fabrication work and how much of the duration is time lost due to disruptions. Reducing the build duration by this delay time provides a fraction of the build duration required to fabricate the closet if all parts were present. The R^2 value for this regression is 0.5544, which indicates that there is a reasonable correlation between the number of parts missing from a kit and the associated increase in late closet completions.

With this information, it is possible to develop an equation to model the reduction in closet build duration based on an increase in the percent of complete kits delivered to the production floor.

$$\Delta = (.23x)\beta \quad (8.2)$$

In this instance, β is the percent increase in the number of complete kits delivered to the production floor, Δ is the change in build duration in days, and x represents the number of missing parts. Equation 8.2 provides the reduction in build duration associated with a percent increase in the complete kits delivered to the production floor, β . It is now possible to modify the process logic in the DES to reflect improved kit delivery by reducing the process time defined by the probability distributions referenced in Chapter 5. It is assumed that all improvements gained from the increased delivery of complete kits will be realized in the final assembly phase of closet fabrication, therefore the change in build duration is applied only to the final assembly logic. Equation 8.3 provides an example of the change in process logic for Program A closet final assembly process.

$$\text{Process Duration} = P(3.58) - \Delta \quad (8.3)$$

In this example, the process logic utilizes a Poisson distribution with parameter of 3.58 and the process logic unit is in days.

With this process, it is possible to iterate the value of β from 0% to 100% to represent improved kit delivery to the production floor. As β increases, the percentage of complete kits delivered increases from 50% to 100%. The β increases in increments of 5%, and the DES is executed for each corresponding β value. Figure 8-3 depicts the results of this process.

8.5 Simulation Results

After executing the DES with the iterated values for the percent of complete kits delivered, several key findings become apparent. As Figure 8-3 indicates, the time required to fabricate a closet (indicated as duration on the figure) decreases as the production floor receives more complete kits and yields an 11.0% reduction when all of the kits delivered are complete.

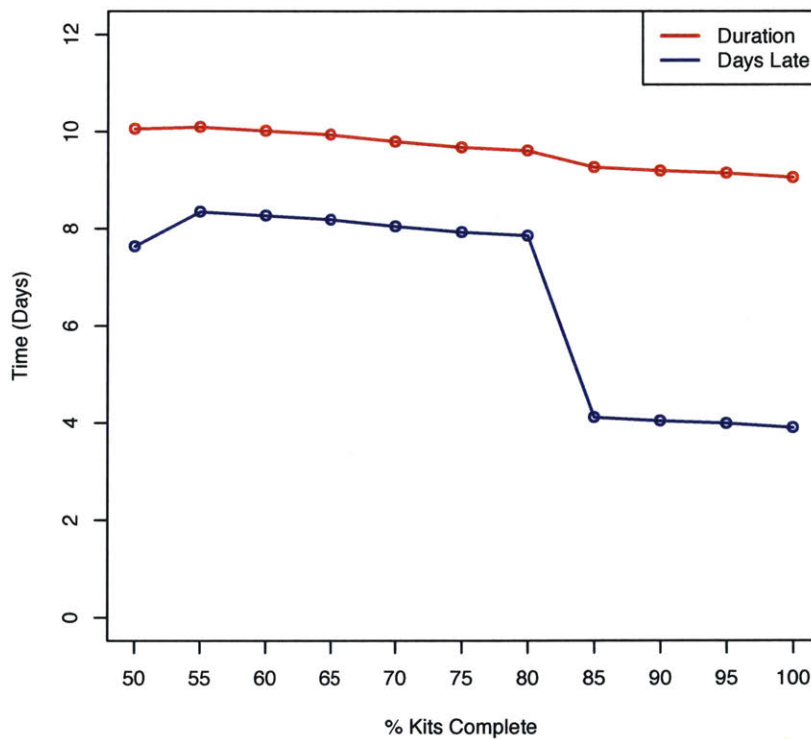


Figure 8-3: Simulation results for improved kit delivery

This result is reasonable given that it takes time to request, locate, and deliver a part if that part is not present when the kit is delivered. The build duration decreases in a nearly linear fashion as the percent of complete kits increases.

While the build duration metric does not provide any surprising results, the late completion metric (listed as days late on the figure) offers some interesting insights. As the percent of complete kits increases, the average number of days late decreases in a linear fashion similar to the decrease portrayed by the build duration metric. However, when the percent of complete kits delivered passes 80%, there is a noticeable step change in the late completion metric. Under the current production system configuration, receiving more than 80% of the kits with all of their required parts yields a nearly 50% reduction in the number of days late that closets are completed.

8.6 Conclusions

These results lead to new conclusions and additional questions. Regarding the step change in Figure 8-3, the reasons behind this outcome are difficult to analyze with precision. It is hypothesized that as more complete kits arrive on the production floor, mechanics spend less time assembling closets (as indicated by the simulation results). This decrease eventually reaches a point where the mechanics can complete closet orders fast enough to create the presence of an additional manufacturing resource on the production floor. The decrease in build duration for all the closets in production equates to adding an additional mechanic to the production system, which leads to the step change in the average late completion for closet orders.

This outcome also provides a valuable insight regarding the current state of the closet fabrication line. Given the current state of operations, significant performance improvements can be achieved by improving the parts delivery process to the point that 85% of the kits delivered by the FF-A warehouse are complete. At this point, the closet fabrication line's performance cannot improve more through improved kit delivery, and another aspect of the fabrication line's operations must be improved. Therefore, the immediate goal for the warehouse managers is to deliver 85% of the kits with all of the required parts. Improving warehouse performance beyond this point becomes necessary only after production system improvements are made and the next operational challenge has been identified and overcome.

These results also indicate that the hypothesis regarding the link between missing parts

and late closet completion is valid. The simulated results provide a clear indication that as more complete kits arrive on the production floor, the time required to build a closet and the number of days late the closets are completed decrease. This finding provides evidence to support testing this theory on the production floor during live manufacturing operations. The next challenge for this research is the development of the tools needed to improve communication and decision making throughout the supply chain.

Part III

Testing Proposed Solutions on the Production Floor

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 9

Selection of Process Changes for Pilot Program Testing

9.1 Pilot Program Background and Intent

Given the findings in Part II, this research considers the process improvements required to improve manufacturing performance. Identifying the required process changes focuses the development of new digital communication and supply chain visibility tools. These tools are then tested on the production floor during a pilot program. This experiment assesses whether the performance gains discovered through simulation are achieved in a live production environment. The results of this pilot program, when compared with the theoretical results derived through simulation, provide the data needed to test this research's hypothesis.

9.2 Pilot Program Requirements and Limitations

The pilot program has several requirements and limitations. The program must test the VML hypothesis in a manufacturing environment without disrupting operations or adding an unneeded burden to the closet fabrication line's mechanics, team leads, and managers. The pilot program's requirements include testing new, data-driven parts request and production queue sequencing tools, maintaining both control group data and an experimental

data set to facilitate an analysis of the experiment's impact, and providing simple and intuitive user interfaces that communicate production system data in a meaningful way to the intended audience. These challenges require the disciplined development and execution of an experimental program that has the support of all of the affected stakeholders and has a robust data collection plan.

9.3 Pilot Program Methodology

The pilot program methodology centers on the development and implementation of two new management tools. These tools inform managers of their production queue, the sequence in which the queue should be executed to minimize late completions, and the current status of inventory in the supporting warehouse. The execution of the pilot program is limited to only closets fabricated for Program A aircraft. This constraint allows this pilot program to focus on a specific area of the closet fabrication line that the management team feels requires the greatest improvement.

9.3.1 Parts Delivery Methods: Push versus Pull

There are two distinct methods to deliver parts in a manufacturing environment: the push system and the pull system. The FF-A warehouse currently delivers parts to the closet fabrication line via a push system, which contributes to the delays and inventory buildup present on the production floor. In their research regarding the implementation of lean principles in low volume, high variability production environments, Bokhorst and Slomp describe the benefit of a pull system:

”The key to the effectiveness of pull systems is that they explicitly limit the amount of work in process (WIP) that can be in a system...the constraints imposed by these lean manufacturing principles simplify the control of the production system and provide motivation to reduce variability in the production system[5].”

The pilot program seeks to transition to a pull system to limit the WIP present on the

production floor and require managers to make data-driven decisions prior to requesting kits for delivery.

Figure 9-1 depicts a push system. Under this system, a production schedule drives parts delivery to the production floor. Under ideal conditions, the push system works well: the final customer (in this case, the airplane program final assembly line) sets a schedule, and the rest of the supply chain performs to meet that schedule. This system breaks down when problems arise in the production process.

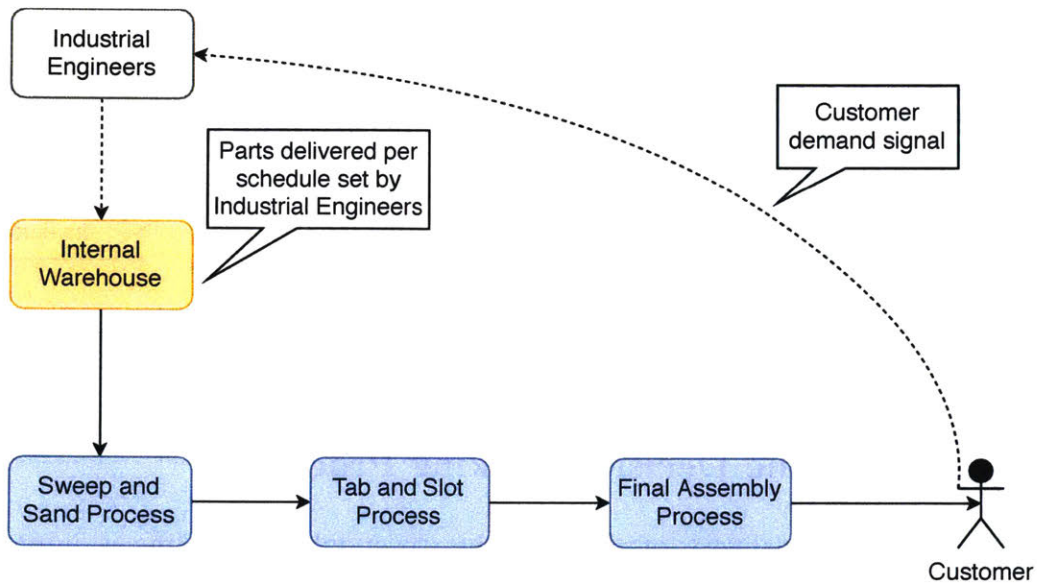


Figure 9-1: Parts delivery via push system

As small disturbances occur, it becomes difficult to synchronize operations from a set schedule. The result is an environment where parts arrive per schedule, regardless of whether the production line needs them. The customer's production schedule is current at the time it is published, but does not reflect or communicate the production floor's inventory needs in real-time. The warehouse delivers parts to the production floor per schedule, which creates the opportunity for excess inventory to accumulate as unneeded parts arrive. The delivery of unneeded parts may also prevent the warehouse from allocating inventory to the proper order in the event the production sequence changes.

Figure 9-2 depicts a pull system for inventory delivery. Under the pull system, each step in the production process communicates its inventory need to the previous step, and only receives inventory when requested. As a result, inventory can be limited through control

mechanisms such as Kanban cards. This system provides a solution to the excess inventory problem that exists on the closet fabrication line, and when combined with the visibility of the supply chain, allows managers to request only the parts they need.

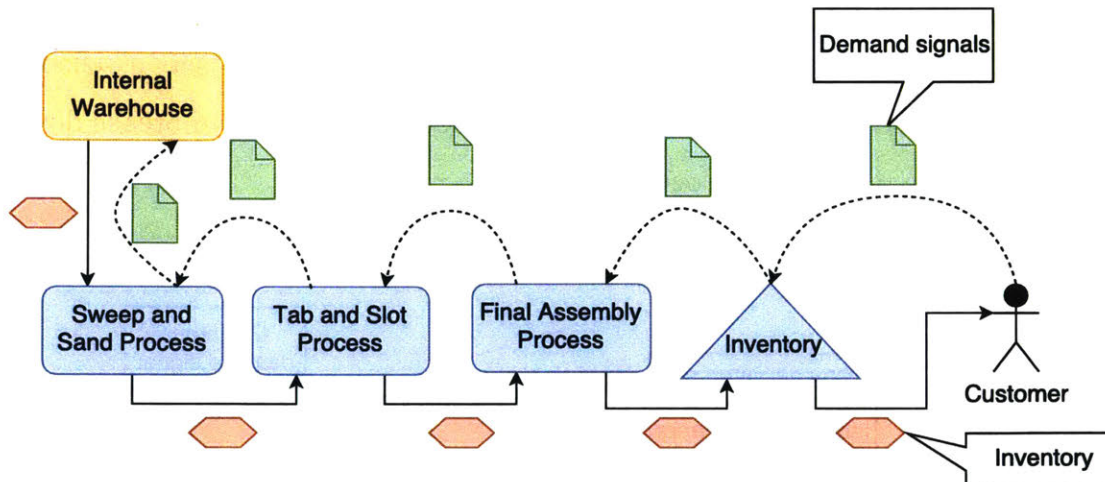


Figure 9-2: Parts delivery via pull system

9.3.2 Improving the Decision Making Process

A key to improving the delivery of parts to the closet fabrication line is improving the decision making process managers use to request and deliver kits. This pilot program tests the utility of additional information in the decision making cycle. In its current state, the closet fabrication line receives kits according to a fixed schedule. Industrial engineers schedule closet order start and end dates, which drive kit delivery. Five days prior to a closet order’s scheduled start date, the industrial engineer delivers a material issue note to the FF-A warehouse management team. The delivery of the material issue note notifies the warehouse to assemble and deliver a closet order kit. The kit must be delivered to the production floor no later than one day prior to the order’s scheduled start date. Figure 9-3 depicts this process.

While the current process transmits a signal from the production floor to the warehouse, the buffer time present in the kit delivery process allows the conditions on the closet fabrication line to change prior to the kit’s delivery. As a result, this process leads to a push system. Providing a prioritized production queue and additional data regarding which parts

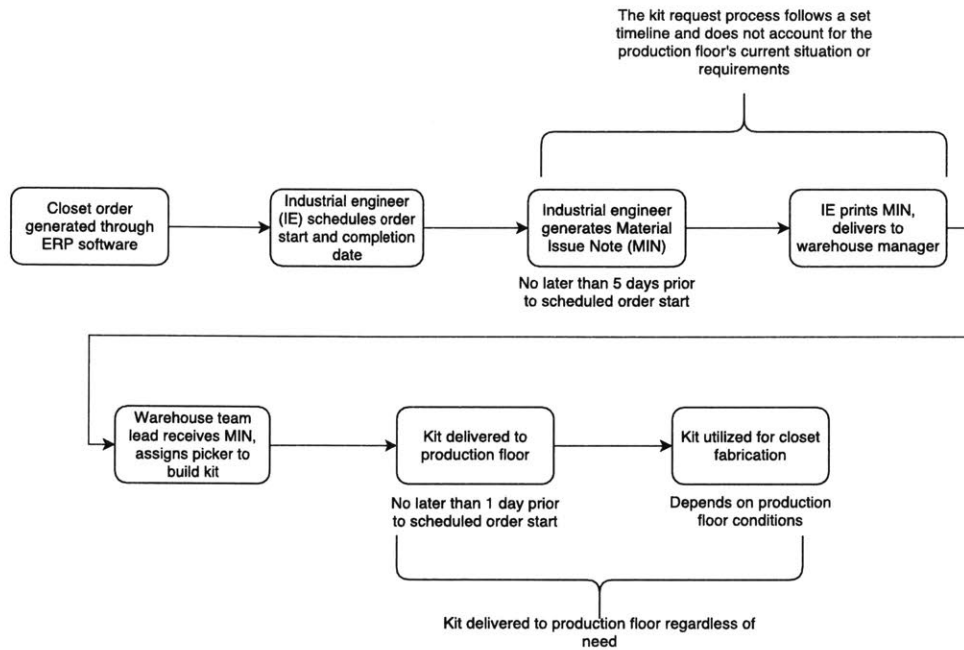


Figure 9-3: Current kit request and delivery method

are available in inventory creates the opportunity to request parts via a pull system. Figure 9-4 depicts the improved kit ordering process. This process utilizes inventory and production system data to select specific kits for delivery and transmits the delivery request digitally to the warehouse manager. Because this system requests kits at the time the closet fabrication line needs them (based on when managers intend to introduce a kit onto the production floor and begin work), the lead time to request a kit reduces from five days to one day.

9.3.3 Evaluation Metrics

The pilot program evaluates the time required to build a closet (build duration), as well as the number of days late closets are completed. These metrics provide a method to analyze the closet fabrication line's performance and assess whether the improvements generated in the DES can be achieved in reality. In addition, the pilot program evaluates the FF-A warehouse's performance by measuring the number of complete closet kits delivered and the number of parts missing from closet kits (both stocked out parts and missing parts). These metrics allow the pilot program to evaluate whether supply chain visibility improves perfor-

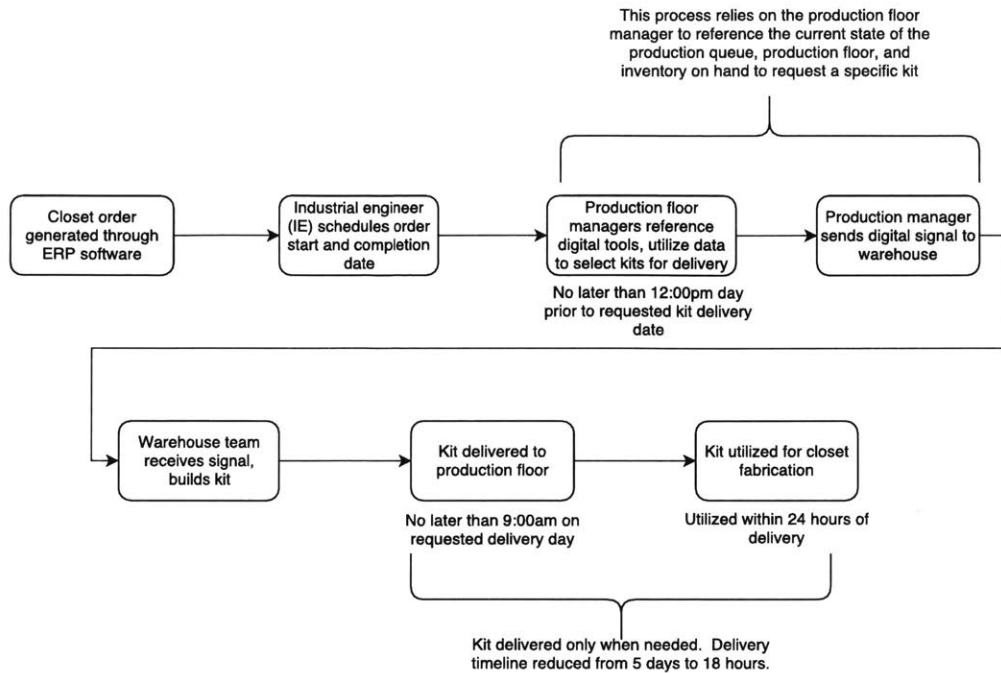


Figure 9-4: Proposed kit request and delivery method

mance across multiple nodes in the supply chain, rather than simply improving performance on the production floor.

9.4 Results and Conclusions

The pilot program establishes two data sets to evaluate the performance of the warehouse and the closet fabrication line. The first data set is a control group. This control group consists of all of the Program A closets completed between June 1, 2017 and November 28, 2017. The control group establishes the current state of performance for the warehouse and closet fabrication line. The experimental data group consists of all the closets produced during the pilot program, which ran from November 29, 2017 to December 8, 2017. This data set is compared to the control group data to determine changes in production floor and warehouse performance. With this data structure and the previously mentioned process improvement goal identified, the pilot program receives approval from the closet fabrication line managers.

Chapter 10

Developing Digital Visibility and Communication Tools

10.1 Background

With approval to execute the pilot program, the research focus shifts to developing the communications and supply chain visibility tools to deliver the performance improvements derived in the digital environment. This challenge requires that the proper data be accessed, aggregated, analyzed, and displayed in a manner that is simple and intuitive for the user. In addition, the correct users must be identified and have access to this data.

Three tools are necessary to provide supply chain visibility. The first tool accesses the current production queue for the closet fabrication line. After accessing this information, the production queue must be prioritized using the slack time per operation method tested in Part II. Once the production queue is in priority order, this information must be presented to managers in the warehouse and on the closet fabrication line.

The second tool provides managers with a current assessment of the parts on hand in the warehouse. This tool considers what items are in the production queue across the FF-A and indicates whether all of the parts required to build a closet are on hand. With this information, the production floor managers can make a deliberate decision as to which closet orders lack the parts needed for assembly and should not be introduced onto the production floor.

The final tool allows the closet fabrication line manager to request a specific closet order kit from the warehouse. This tool reflects the prioritized production queue and allows the production floor managers to pass a digital signal to the warehouse requesting delivery of a specific kit.

10.2 Visibility Tool Problems to Solve

There are several challenges associated with developing these tools. First, the tools must access the needed information, execute the prioritization heuristic, and evaluate the inventory on hand in the warehouse correctly. Next, the tools must display this information in a simple and intuitive form. Finally, the information must be passed digitally between two nodes in the supply chain in a manner that prevents information loss and generates a specific action from a specific person upon receipt.

10.3 Visibility Tool Development Methodology

The digital tools that support the pilot program require the use of common software that provides a simple, intuitive user interface. The software tool must also support data entry by the user to pass signals between the warehouse and the production floor, which, in this instance, leads to the need for two digital communication tools. The first tool displays the aggregated data and allows the user to view the prioritized production queue. Data visualization software fulfills this need and allows for rapid changes to the user interface based on user feedback. To support the data entry requirement, a website that reflects the prioritized production queue and accepts simple user inputs is sufficient. In this instance, Tableau and SharePoint, respectively, are chosen. These programs fulfill the requirements above and Boeing employees use these software packages frequently.

10.4 Solutions Developed to Support the Pilot Program

The initial tool designs are tested for functionality and then demonstrated to the intended users. User feedback indicates that reducing the amount of information displayed on each tool is necessary to avoid confusion. The following designs are the result of several iterations. Figure 10-1 depicts the dashboard that indicates the prioritized production queue with inventory status.

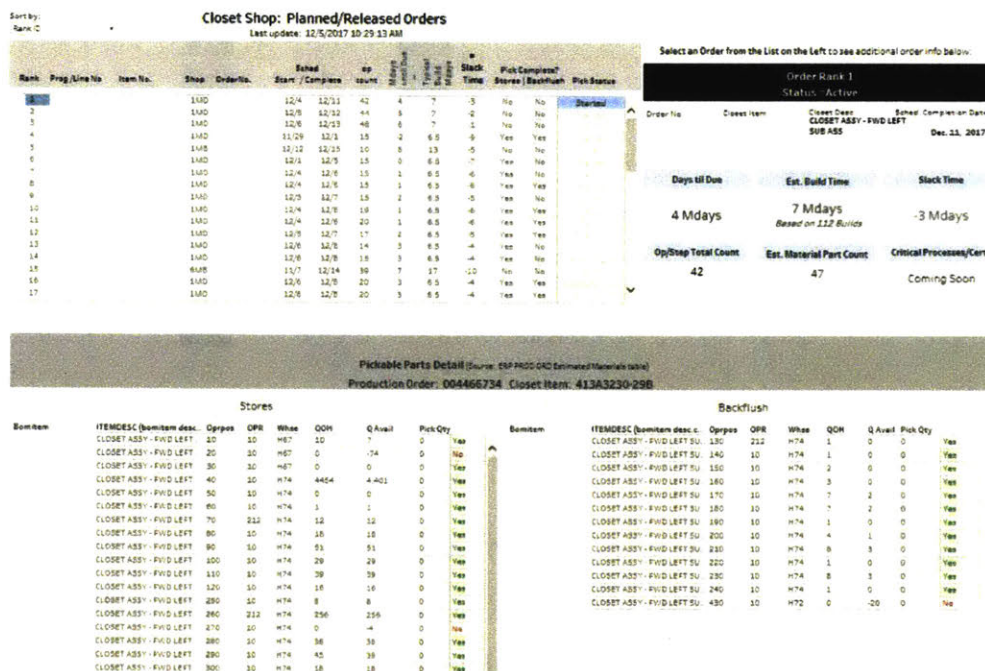


Figure 10-1: Dashboard depicting the prioritized production queue and inventory status. Program, order number, and line number data are obscured to protect proprietary information.

This tool allows the closet fabrication line leaders, the warehouse managers, and the warehouse picker to view the production queue in its prioritized sequence as defined by the slack time per operation method discussed in Part II. This dashboard also indicates whether the parts required to build a closet order are currently on hand in the FF-A warehouse. In addition, a user may select a specific closet order and view that order's complete BOM. This digital tool allows the closet fabrication line manager to select which closet orders to build next, based on the prioritized queue and the current inventory status in the warehouse.

Figure 10-2 depicts the second tool required to execute the pilot program. This website allows the closet fabrication line manager to select which kits the warehouse should deliver the following day.

Stop editing this list

Rank_ID	Order Number	ItemID	Start Date	LN	Request_Pick	Request_Recvd	Out_for_Delivery
1			12/4/2017		Yes		Yes
2			12/5/2017		Yes		
3			12/4/2017		Yes		
4			11/29/2017		Yes		Yes
5			12/12/2017				
6			12/1/2017		Yes		Yes
7			12/7/2017				Yes
8			12/6/2017				Yes
9			12/5/2017		Yes		Yes
10			12/5/2017		Yes		Yes
11			12/7/2017		Yes		Yes
12			12/5/2017		Yes		Yes
13			12/6/2017				
14			12/6/2017				
15			11/7/2017				
16			12/1/2017				
17			12/6/2017		Yes		
18			12/7/2017				
19			12/4/2017		Yes		
20			12/8/2017				
21			12/8/2017				
22			12/1/2017				Yes
23			12/11/2017				

Figure 10-2: SharePoint site to request kit deliveries

Order number and line number data are obscured to protect proprietary information

The dashboard does not allow users to enter and store data, which necessitates the use of this tool to communicate kit delivery requests. By selecting the boxes in the far left column and indicating "Yes," the production floor manager sends a signal to the warehouse that the production floor requires a specific kit. The warehouse manager and picker view this website and receive these signals from the production floor. Upon receipt of this signal, the warehouse picker prepares the kit for delivery by picking the BOM from inventory. When the kit is complete and placed in the warehouse outbound parts area, the picker indicates this status by changing the far right column to "Yes." This signal indicates that the requested kit has been picked and is awaiting delivery. This tool facilitates two-way communication between these two nodes in the supply chain and provides the information conduit necessary to implement a pull system. With these two tools available, the pilot program is ready for execution in a production environment.

When compared to the original VML dashboard, the new tools focus on different aspects

of the production system and provide more focused information to the user. The original dashboard, depicted in Figure 2-2, provides a detailed view of the production floor's current state. The new tools focus less on defining the current state and more on informing managers of the ability of elements outside the production line to support the production line's future operations. This change communicates the status of the supply chain in a manner that allows each node to understand the other nodes' current status and how that status impacts upcoming operations.

10.5 Results

The tools developed to support the pilot program are demonstrated for the warehouse and production floor managers. Their feedback leads to several iterations until the tools are simple enough to prevent confusion, yet provide the information needed to request and fulfill kit orders. This iterative design process indicates that order number, start dates, closet model, and aircraft model are essential pieces of information that allow the warehouse to label and deliver kits efficiently. This iterative process also indicates that the large number of Program A closet orders require the closet fabrication line to refer to closet orders by aircraft line number rather than by closet model number. Using the aircraft line number to identify a closet kit simplifies the communication process within the production floor.

10.6 Conclusions

While software limitations require the use of two separate digital tools to display and communicate information throughout the supply chain, the user feedback and positive responses to these tools indicate that the tools are simple and effective. These findings support the decision to execute the pilot program. It is also important to note that designing and developing digital tools for a manufacturing environment requires frequent feedback from the intended users. Without this feedback, it is very difficult to create a tool that solves the problem inhibiting an operations leader from accomplishing a task.

Based on the feedback received regarding the users' interest in viewing specific production

system information, it is possible to develop a unique conclusion regarding the users' intent for utilizing this data. Improving the users' situational awareness of the production queue and the status of each closet order creates the opportunity for managers to prevent a closet order from falling behind schedule and requiring additional effort (in this case overtime labor) to get back on schedule. Taking initiative early to avoid a late closet delivery is analogous to a control system that governs the motion of an accelerating body.

As the body accelerates, its velocity increases, which leads to an increase in momentum. This momentum increase makes it more difficult to bring the body to rest, which is a similar challenge faced on the closet fabrication line. As a closet order falls further behind schedule, it takes more management effort and more overtime labor to correct the deficiency and bring the closet order back onto schedule. The digital visibility tools developed in this chapter provide managers with situational awareness of which closet orders are likely to fall behind schedule. Understanding which parts are missing from a closet order before the order is behind schedule allows the manager to take action and rectify the situation before overtime labor or an expedited order from a supplier become necessary. For this proactive behavior to be effective, information must be provided to the manager in cycles that are shorter in duration than the time required to manage the production cycle. In this state, the manager receives information frequently enough to improve decision making and take action to avoid disruptions in the production system.

Chapter 11

Pilot Program Development and Execution

11.1 Pilot Program Execution Background

The next phase of this research is the development and execution of the pilot program. In agreement with the closet fabrication line and warehouse management teams, an eight day pilot program is planned to gather data from the Program A closet production line. During this experiment, the closet fabrication line managers, warehouse manager, and warehouse picker utilize the two digital communication tools to select which closet orders to build next, request the required kits, and identify which kits to pick and compile in the warehouse. At the request of the closet fabrication line manager, the pilot program applies only to closet orders for Program A aircraft. Due to the large number of Program A closet orders and the high production rates for Program A aircraft, the Program A closet line is a main focus for process improvement and allows for the largest amount of data to be collected in the shortest period of time.

11.2 Pilot Program Challenges and Limitations

The pilot program intends to change the method for delivering parts from the warehouse to the production floor from a push system to a pull system. Doing so without disrupting

the production floor is a significant challenge and requires the development and utilization of standard work during the test phase. While this pilot program provides an opportunity to test the new VML tools, it does have several limitations. The time required to fabricate a closet ranges from four to ten days, and the production line finishes between one and two Program A closets per day. Ideally, a pilot program runs for enough time to allow multiple fabrication cycles to occur during the experiment. This approach allows the users to learn the new tools, become comfortable with the new process, and generate consistent data without interference from a new system. In addition, a pilot program that allows the production floor to complete more orders generates more data, which increases the confidence level of the results. Due to time and operational constraints, it is not feasible to execute the pilot program beyond eight days. While an eight day pilot program yields a small sample of closets and does not allow the users to execute the process over multiple cycles, the results provide an initial analysis of the VML concept's utility and inform the decision to pursue a longer pilot program in the future.

11.3 Execution Methodology

Prior to beginning the pilot program, standard work is developed to govern the use of the digital tools and to ensure that each member of the experiment understands his or her roles and responsibilities. The following section details the pilot program's execution plan.

11.3.1 User Roles and Responsibilities

During the pilot, there are four key individuals who interact with the digital tools, send and receive signals, and make decisions based on the data presented on the production queue dashboard. The closet fabrication line manager and the Program A closet assembly team lead are the key personnel representing the production floor, and the FF-A warehouse manager and the closet fabrication line parts picker represent the warehouse.

The closet fabrication line manager and Program A closet assembly team lead view the production queue dashboard each morning at the start of the first shift. At this time, they assess the current state of the production floor, determine how many closet orders to

start, and identify which kits to request next based on the prioritized production queue and associated inventory status. No later than 12:00pm daily, the closet fabrication line manager submits requests for the kits needed for the following morning to the warehouse using the website tool. These individuals then monitor the website for updates from the warehouse picker indicating that the requested kits are out for delivery.

The warehouse manager and closet parts picker execute a similar standard work package. At 12:00pm daily, the closet parts picker checks the website to receive the pick requests from the closet fabrication line. The picker assembles the requested kits that afternoon and prepares them for delivery the following morning. In addition, the closet parts picker and the warehouse manager monitor the prioritized production queue and identify which closet orders are of high priority with all of the required parts on hand in the warehouse. The warehouse manager and the picker decide which kits to prepare based on priority level and parts availability, and hold these kits in the warehouse until the closet fabrication line manager requests them. The warehouse establishes a distinct holding area for pre-picked closet order kits. Kits picked in advance of a request from the production floor are held in this area until requested to support the transition from a push system to a pull system for parts delivery. Table 11.1 depicts the pilot program standard work sequence.

Table 11.1: Pilot program standard work and execution sequence

Time	Event	Initiated By	Received By	Tool
5 am	Production queue dashboard checked	Production line manager	N/A	Production queue dashboard
No later than 12 pm	Kit request submitted	Production line manager	Warehouse picker	Kit request website
No later than 4 pm	Picker builds requested kits	Picker	Warehouse distribution	N/A
No later than 4 pm	Picker indicates kits out for delivery	Picker	Production floor manager	Kit request website
No later than 9 am (next day)	Kit delivered	Warehouse distribution	Production floor manager	N/A

11.3.2 Pilot Program Execution

The pilot program utilizes this standard work to limit the impact of a change in inventory delivery on the production system. By defining the timing of each action and the individuals responsible to execute each action, the pilot program limits the opportunities for a missed parts delivery or other production system disturbance. The pilot program also codifies that parts requested by 12:00pm are delivered the following morning by 9:00am. This cadence creates predictability for both the production floor and the warehouse, and establishes a common expectation across the supply chain. In addition, the pilot program establishes a limit on the number of kits that the production floor requests in one day to avoid exceeding the warehouse's capacity to build and deliver kits. The two elements agree to request no more than five kits per day, which satisfies the production floors takt time and fits within the warehouse's current capacity constraints.

In the event of an issue with the pilot program, the previous kit ordering system remains in place. The closet fabrication line industrial engineer continues to deliver material issue notes to the warehouse throughout the pilot program. The material issue notes serve as a backup plan to avoid disrupting the production system in the event that one of the pilot program tools does not work as intended.

11.4 Data Collected during Pilot Program

Three data sets facilitate the assessment of the pilot program. The first data set includes all of the closets fabricated from June 1, 2017 to November 28, 2017. This data set establishes the current state of operations for the closet fabrication line and includes the closets built for all airplane programs. The second data set includes only Program A closets built from June 1, 2017 to November 28, 2017. This second data set serves as the control group against which changes are measured, while the first data set provides a benchmark to compare the performance of the Program A closet line during the pilot program against the entirety of the closet fabrication line. The final data set consists of the closet orders built during the pilot program.

11.4.1 Data Collection Plan

The eight-day pilot program yields a data set that includes production system data and key metrics for ten closets. These ten closets are fabricated from kits requested using the digital visibility and communications tools. Several metrics are utilized to compare the production system's performance before and during the pilot program. The time required to fabricate a closet (duration) is measured, as is the number of days late closets are completed when compared to their scheduled completion date (days late). The number of parts missing from closet order kits is also measured and broken into three categories. First, the number of parts not available due to stock-outs (SOS parts) is recorded. Second, the number of parts requested through the MPR system is noted. Finally, the total number of missing parts (total missing parts is the sum of the number of stocked out parts and the number of MPR requested parts) is recorded. The before and after values of these metrics are compared to assess changes in warehouse and production floor performance.

11.4.2 Consolidated Data Findings

The following tables and graphs depict the pilot program data and compare it to the control group. Table 11.2 summarizes the key metrics for the control group closets, while Table 11.3 summarizes the key metrics for the closets built during the pilot program.

Table 11.2: Closet build durations before the pilot program

# Parts Missing	Mean Duration	# Observations
0.00	7.33	69
1.00	7.56	43
2.00	8.44	25
3.00	7.71	17
4.00	6.78	9
5.00	7.58	12
6.00	8.33	3
7.00	9.50	2
8.00	10.00	2
9.00	7.00	1
10.00	5.00	1

Table 11.3: Key characteristics of closets built during the pilot program

# Parts Missing	Mean Duration	# Observations
0.00	7.00	8
1.00	10.00	1
2.00	10.00	1

Figure 11-1 compares the build duration density distributions for both groups of closets, while Figure 11-2 compares the density distributions of late closet completions.

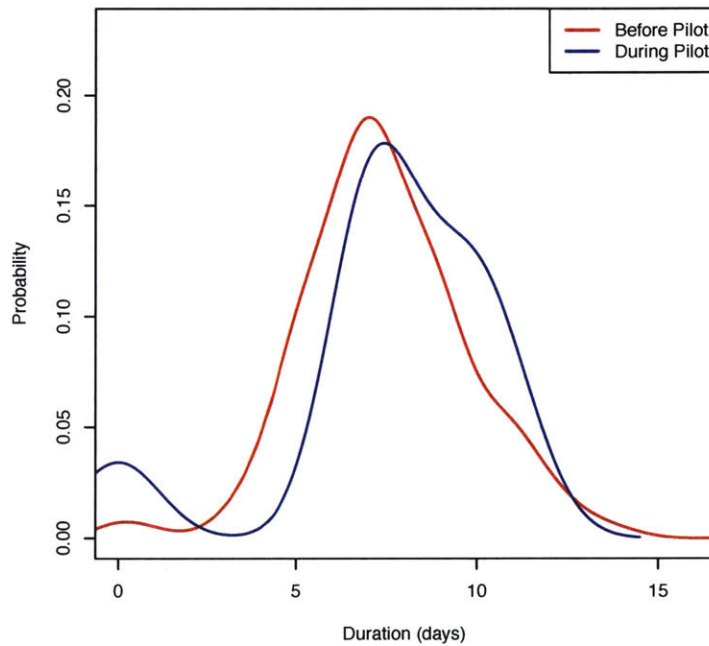


Figure 11-1: Comparison of build durations before and during the pilot program

Table 11.4 reports the mean and standard deviation for the key metrics described above. These data reflect the closet fabrication line’s performance during the assembly of ten closets during the pilot program.

11.5 Results and Analysis

11.5.1 Initial Observations

Based on these data, several results are apparent. A visual analysis of the data in Figures 11-1 and 11-2 does not indicate a significant decrease in the time required to build a closet,

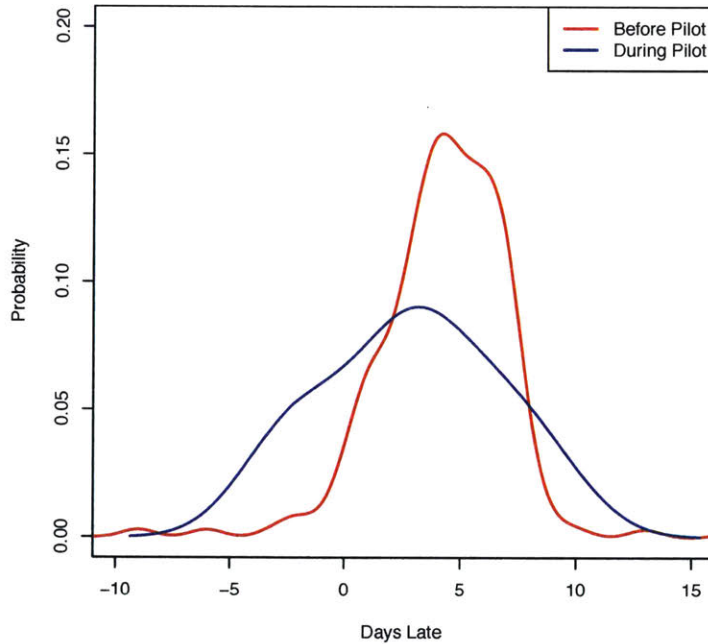


Figure 11-2: Comparison of late completion days before and during the pilot program

while the number of days late closets are completed appears to shift towards more timely completions.

These initial observations indicate that the closet fabrication line becomes closer to achieving its completion deadlines, but does not significantly reduce the time required to assemble a closet. An interesting finding in these results is the production line's early completion of some closets. The production line completes several closets ahead of schedule, as Figure 11-2 indicates. The presence of early order completions in an environment where late orders also exist indicates the production line still faces challenges in sequencing its work. Ideally, the production line completes all of its orders on time, rather than some orders early and some orders late. The presence of a late order and an early order implies that the production line could have managed its schedule or resources in a more efficient manner to deliver all orders on their assigned completion dates. While the VML prioritization tool appears to make a positive impact on late completions, an opportunity for further improvement exists.

Figure 11-3 plots the build durations and the late completion days versus the percent of complete kits delivered for the pilot program closets and compares these outcomes to the theoretical results determined through the discrete event simulation (Chapter 12 examines

Table 11.4: Mean and standard deviation of key performance metrics

Item	Current State	Before Pilot	During Pilot
Number of Closets Built	482.00	184.00	10.00
Mean Days Late	4.18	4.29	2.90
Days Late Std Dev	4.10	2.84	3.84
Mean SOS Parts	0.70	0.55	0.30
SOS Parts Std Dev	1.30	1.05	0.67
Mean MPR Parts	1.48	1.12	0.00
MPR Parts Std Dev	2.46	1.69	0.00
Mean Total Parts	2.18	1.67	0.30
Total Parts Std Dev	2.85	2.01	0.67

the differences in the simulated and actual results in detail). From this plot, it is clear that during the pilot program the time required to fabricate a closet and the number of days late the closets are completed decreases as the percent of complete kits delivered increases.

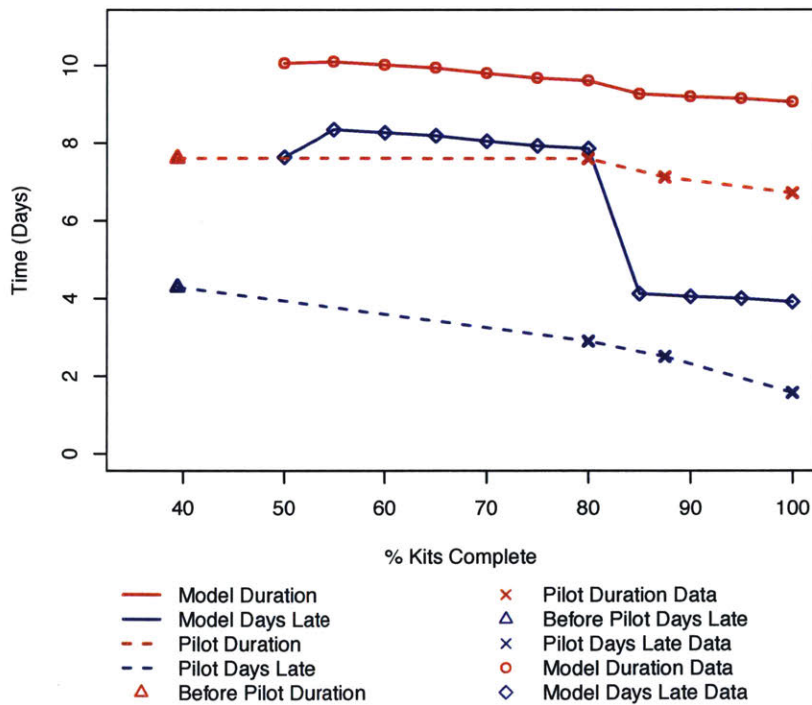


Figure 11-3: Pilot program and simulation results

This trend exists for both metrics and provides visual evidence that improving supply chain visibility and delivering kits through a pull system improves the closet fabrication line’s performance. During the pilot program, the average time required to fabricate a closet

decreases by 11.3% from 7.9 days (current state of operations) to 7.0 days (best performance achieved for kits that were delivered complete). In a similar fashion, the average number of days late closets are completed decreases from 4.3 days to 2.9 days, which constitutes a 32.5% decrease. These changes indicate that the closet fabrication line’s performance improved noticeably during the pilot program.

It is also necessary to assess the impact the pilot program has on the warehouse’s performance. The number of parts stocked out (SOS parts) decreases from 0.55 parts/kit to 0.30 parts/kit, while the number of parts missing from kits (MPR parts) decreases from 1.12 parts/closet to 0 parts/kit. The total number of parts missing from a closet kit (the sum of the SOS and MPR parts) decreases from 1.67 parts/kit to 0.30 parts/kit during the pilot program. In addition, the percent of complete kits delivered to the closet fabrication line increases from 39.4% (an average value for the control group data set) to 80.0% (an average value for the pilot program data set) during the pilot program. Tables 11.4 and 11.5 summarize these results. While these initial findings are encouraging, it is necessary to examine these results using statistical analysis techniques to verify the statistical significance of these improvements.

Table 11.5: Percent of complete kits and associated completion days late

Scenario	# Built	# Complete	% Complete	Mean Days Late	Mean Duration
Current	472	145	30.7	4.2	8.99
Control	175	69	39.4	4.3	7.9
Pilot	10	8	80.0	2.9	7.60

11.5.2 Hypothesis Test Results

To assess the statistical significance of the results described above, a hypothesis test is executed using a two-sided t test. This hypothesis test states a null hypothesis that the difference in mean values between the control group metrics and the pilot program metrics is 0 (see Equation 11.1), while the alternative hypothesis states the difference in mean values is not equal 0 (see Equation 11.2).

$$h_0 : \mu_{pilot} - \mu_{control} = 0 \tag{11.1}$$

$$h_1 : \mu_{pilot} - \mu_{control} \neq 0 \quad (11.2)$$

Executing the t test with a 95% confidence level produces the results in Table 11.6.

Table 11.6: Pilot program hypothesis test results

Estimate	t-Stat	p Value	Conf Int Low	Conf Int High	t Crit	Scenario
0.01	0.01	0.99	-2.20	2.23	1.97	Build Duration
1.39	1.13	0.29	-1.37	4.16	1.97	Days Late
0.25	1.10	0.30	-0.25	0.75	1.97	SOS Quantity
1.12	8.96	0.00	0.87	1.37	1.97	MPR Quantity

Based on these results, it is necessary to reject the null hypothesis for the build duration, days late, and stocked out parts (SOS) quantity metrics. This test fails to reject the null hypothesis regarding the difference in means for the parts missing (MPR) metric.

These findings indicate that there is a statistically significant difference in the time required to build a closet, the number of days late closets are completed, and the number of stocked out parts per kit recorded during the pilot program. All three of these metrics decrease (and therefore improved) during the pilot program. The number of parts missing (MPR) from kits did not experience a statistically significant change during the pilot program.

It is important to note that these results are based on a small sample of closets (10 orders) constructed during the pilot program. Ideally, a larger sample of closet orders forms the basis for this statistical analysis; however, it is not possible to collect additional data due to time constraints. This small sample size limits the utility of statistical testing, but does provide an initial indication that the data analysis and visualization tools lead to improved production floor performance. While it is not possible to place complete confidence in these results, the outcome does provide reason to execute future testing to collect additional data and generate more conclusive results.

11.6 Conclusions

Based on these results, it is possible to conclude that prioritizing the production queue, providing visibility of warehouse inventory levels, and sharing this information across the supply chain has a positive impact on production system performance. While the experimental data set is small, the statistically significant reductions in three of the four key performance metrics indicate that providing managers with meaningful production system data has the potential to yield positive improvements in manufacturing performance. In light of this potential for improvement, these results justify additional experimental testing to collect a larger data set and validate these initial findings.

A key finding in these results is the identification of the data managers require to improve operations. The initial VML hypothesis states that access to data improves performance, but the hypothesis does not identify what data managers need to achieve these improvement. The results of this research fill this gap in the original hypothesis by determining that data regarding inventory on-hand, the production queue, and the priority of the orders in the production queue are useful and enable managers to improve their operations.

The pilot program also provides insights regarding the use of performance metrics. Pilot program observations indicate that the current warehouse performance metric regarding the on-time delivery of kits to the production floor has shortcomings when measuring performance in a pull system. The pull system requires that parts arrive when they are requested, and works best when lead times are short and the warehouse responds quickly to requests for parts. Measuring whether a part arrives on the correct day proves to be too coarse of a metric, and in several instances, the production floor waited several hours to receive parts intended for delivery at the start of the morning shift. While the build duration and days late metrics quantify the production floor's performance, it is also important to quantify the warehouse's performance by measuring the on-time delivery of parts to the production floor. This metric must utilize hours and minutes as its time scale, rather than days, to measure performance and incentivize the on-time deliveries needed to support a pull system.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 12

Simulation and Pilot Program Results Comparison and Findings

12.1 Results Comparison Background and Motivation

The results and conclusions in Chapter 11 indicate meaningful improvements in production system performance when the proper information is available to managers across the supply chain. While these results are encouraging, it is also necessary to assess whether the results meet the expectations set by the discrete event simulation. The simulation, while an approximation of the actual production system and an idealized state of operations, establishes the level of improvement that is possible under ideal conditions. The real production environment is clearly not ideal, and identifying the sources of difference between the simulated and actual results informs future changes and continuous improvement initiatives.

12.2 Problem to Solve

The challenge in this analysis is assessing the difference in the simulated and pilot program results, determining the sources of the difference, and recommending actions to reduce or eliminate the discrepancy. Under ideal conditions, a properly constructed simulation and well executed improvements on the production floor yield similar results. If not, there may be issues with the discrete event simulation or problems executing the changes properly on

the production floor.

12.3 Results Comparison Methodology

Assessing the differences between the simulated and actual results requires a side-by-side comparison of key metrics. Plotting the simulation and pilot program provides a simple method to assess whether trends appear in both data sets and the differences in magnitude and direction of the trends. It is also necessary to iterate the percent of complete kits delivered to the closet fabrication line to assess the hypothesis that a higher percentage of complete kits improve production system performance. Performing this iteration in the discrete event simulation is simple: the percent of kits is incremented and the simulation executed for each percentage of kits complete. However, this iteration is more difficult to perform during the pilot program. It is not feasible to instruct the warehouse to send incomplete kits to the closet fabrication line intentionally, as this action would disrupt manufacturing operations. As a result, fewer data points are available for the pilot program results, and these data points do not cover as wide a spectrum of warehouse performance levels as the simulated results.

12.4 Comparison Data

Figure 12-1 (this is the same plot as Figure 11-3. The plot is reproduced for ease of reading.) depicts the combined results of the simulation and pilot program for the two key performance metrics.

12.5 Findings and Results

Figure 12-1 indicates several clear trends in the simulation and pilot program results. The most noticeable difference in the results are the magnitudes of the outputs. The simulated build duration and days late results are greater than the results recorded during the pilot programs. The build duration results are 25% different, while the days late differs by nearly

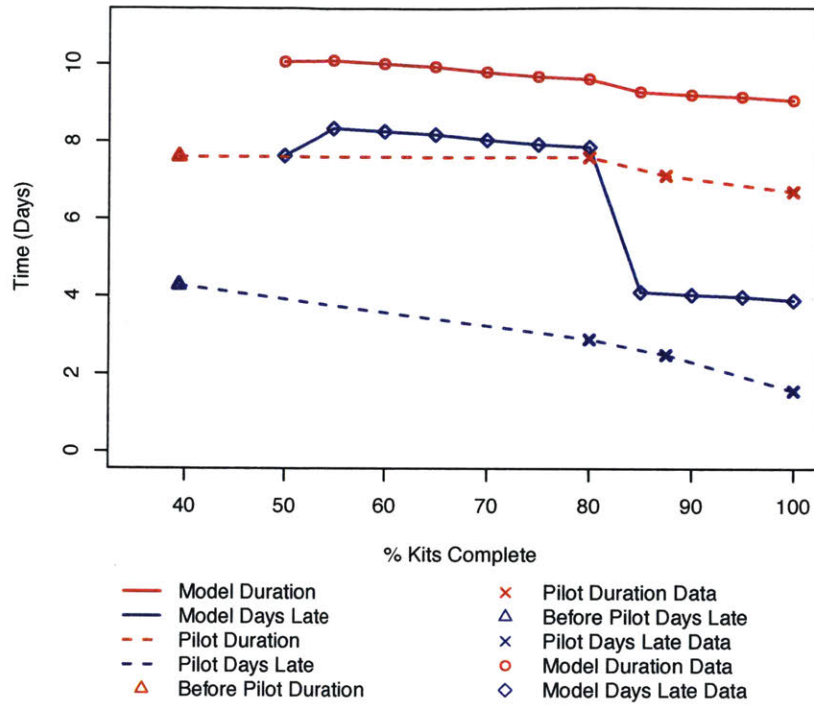


Figure 12-1: Pilot program and simulation results

100%. The assumptions made when developing the DES account for these differences.

The DES assumes the closet fabrication line utilizes no overtime labor. As a result, all of the fabrication work occurs on a manufacturing day, which increases the duration of a closet build. In reality, the closet fabrication line utilizes overtime labor, and this time is not recorded as occurring on a separate manufacturing day; instead, the overtime work is recorded on the most recent preceding manufacturing day. This fact reduces the recorded number of days required to fabricate a closet during the pilot program and provides an explanation for the increased time required to build a closet in the simulation. If the closet fabrication line utilizes two overtime shifts on a Saturday, the production line gains an additional manufacturing day of labor, which effectively increases the number of manufacturing days per week from five to six. This difference leads to a 20% increase in the available manufacturing time per week, which provides a reasonable explanation for the 25% difference between the simulation and pilot program results for this metric.

This difference also impacts the number of days late a closet order is completed. Late orders receive priority for additional mechanic effort during overtime shifts to minimize

tardiness, and this effort is not recorded as work occurring during a separate manufacturing day. If the closet is completed during an overtime shift, the closet appears to have been completed on the most recent manufacturing day, further reducing the number of days late present in the data.

Despite these differences, the trends in the data appear quite similar and provide useful insights into the impact of parts availability on production system performance. In both the simulation and pilot program results, the time required to build a closet decreases and the number of days late closets are completed decreases as the percent of complete kits delivered to the production floor increases. It is also clear in both data sets that the greatest improvement in performance occurs when the percent of complete kits delivered exceeds 80%; however, the step change predicted by the simulation does not occur in actuality. Prior to reaching the 80% threshold, production system performance remains constant in terms of closet build durations, while the number of days late decreases slightly. Unlike the DES results, production system performance continues to improve as the percent of complete kits delivered increases past 80%.

Despite the difference in magnitudes present in the data sets, the relative change in performance metrics is similar across both sets of data. Table 12.1 compares the percent change in closet build durations as the percent of complete kits increased from the current state to 100%.

Table 12.1: Build duration improvement, simulation and pilot program results

Scenario	Current State	100% Complete Kits	% Change
Simulation	10.0	8.9	11.0%
Pilot Program	7.9	7.0	11.3%

The magnitude of the duration values is different, but the percent change for the two scenarios is very similar. This finding indicates that while there are differences between the simulation and the actual production floor, the pilot program results match the expected percent reduction in build duration predicted by the DES. Table 12.2 reports the same data comparison for the completion days late metric.

Once again, there is a clear difference in the magnitude of the metric values, but the percent change in the values is similar. The production floor does not perform as well as

Table 12.2: Days late improvement, simulation and pilot program results

Scenario	Current State	100% Complete Kits	% Change
Simulation	7.8	3.9	50.0%
Pilot Program	4.3	2.9	32.5%

the simulation predicts (50%), but a 32.5% improvement is a strong improvement. The difference in the actual and expected improvement can be accounted for by the structure of the pilot program. This program tests the selection and delivery of kits to the production floor only. The pilot program does not attempt to maintain a priority score for each closet order throughout the production process; however, the simulation maintains and updates these priority scores as the order travels through the production system. As a result, it is possible that the closet fabrication line does not pass closet orders through the production floor in priority order, which would lead to a less significant performance improvement.

12.6 Conclusions

Overall, the improved delivery of parts to the closet fabrication line leads to the expected percent change in the performance metrics the DES predicts and provides evidence that the initial hypothesis is valid. As previously stated, the small data sample collected during the pilot program does not provide conclusive results to confirm the hypothesis, but these results are encouraging and justify the execution of a longer pilot program to collect more data and confirm these initial findings.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 13

Key Results and Conclusions

13.1 Review of Research Background and Goals

This chapter reviews the initial hypothesis that motivates this research and summarizes the previous chapters' key findings and conclusions. This research intends to test the hypothesis that providing data to managers on the manufacturing floor improves decision making and creates improvement in the production system's performance. In addition, this research assesses what information managers require to achieve these improvements and concludes with a pilot program that tests this hypothesis on the production floor.

13.2 The Parts Delivery Problem

An extensive observation of the closet fabrication line, interviews with mechanics, team leads, and managers, and a quantitative analysis of historical production data lead to the conclusion that the delivery of incomplete kits negatively impacts the production line's performance. The delivery of incomplete kits appears to be one of several causes of behind schedule closet completions, the need for overtime labor, and the presence of excess WIP on the production floor. This finding generates a refined hypothesis that providing visibility of the supply chain utilizing data analysis improves management decision making, allows for the implementation of a pull system to deliver kits, and reduces both the time required to fabricate a closet and late closet completions. Utilizing production system data to implement

these countermeasures not only serves as a method to improve closet fabrication operations, but also provides a means to evaluate the VML hypothesis.

13.3 Key Results and Conclusions

13.3.1 Information Improves Decision Making

The presence of information regarding inventory status and production queue priority has a beneficial impact on the closet fabrication line's performance. The DES predicts that the time required to build a closet decreases by 11.0% when all of the kits delivered to the closet fabrication line are complete. By providing a means to evaluate current inventory levels, assess order priority, and communicate requests for specific kits throughout the supply chain, the pilot program reduces the time required to build a closet from 7.9 days to 7.0 days (when 100% of the kits delivered are complete), resulting in a 11.3% decrease. This result supports the hypothesis that decision making improved with access to data.

Similar results occur with regard to the number of days late closets were completed when managers had access to data. While the simulation predicts a 50% reduction in the number of days late, the pilot program produces a decrease of only 32.5%. The use of overtime labor is a likely source of this discrepancy. Much like the build duration data, this metric confirms the hypothesis that providing managers with access to data allows them to make better decisions and improves operations.

The final result of interest is the increase in the percent of complete kits delivered to the production floor during the pilot program. The control group data indicates that 39.4% of kits are delivered complete prior to the start of the pilot program. During the pilot program, this value increases to 80.0% for the ten closets built. This increase indicates that access to the inventory data improves management decision making and leads to a significant improvement in warehouse performance.

These findings indicate that the initial hypothesis is valid; however, due to the small sample of closets built during the pilot program, these results are preliminary and require additional validation through a more robust pilot program.

13.3.2 Limited Link between Data Access and Urgency

One aspect of the VML hypothesis is the creation of urgency in the workforce when data is accessible on the production floor. While performance improves in the presence of data, it is difficult to attribute this improvement to a greater sense of urgency in the mechanics and managers. There is no evidence that accessing data leads to increased urgency in the managers, but it does appear that access to data allowed for the implementation of sound manufacturing principles (pull system, starting work only when parts are present). These principles allow the managers to make better decisions and work together to deliver all of the required parts, at the required time, to the required location.

13.3.3 Proper Fundamentals Matter

While the data analysis and visualization components of this research provide important insights into the use of emerging technologies in manufacturing, it is important to note that this technology enables the application of basic operations principles. The use of a pull system to deliver inventory, communication throughout the supply chain, creating a common production queue, and starting work only when all of the required parts are available are fundamental best practices for operations and manufacturing. The application of new technology serves as a compliment, rather than a replacement, for these bedrock principles. If an organization struggles to execute these fundamentals well, the manufacturing process suffers. This research indicates that the initial VML hypothesis is sound and in the case of the closet fabrication line, digital communication and visibility tools improve operations performance while providing managers with the opportunity to implement manufacturing best practices. The combination of sound manufacturing principles, combined with data analysis and visualization tools, leads to positive performance improvements for the closet fabrication line.

THIS PAGE INTENTIONALLY LEFT BLANK

Glossary

final assembly The final process for closet fabrication. During this process, mechanics finish joining the closet's exterior components, install interior components and electrical components, and add any remaining decorative items or laminate. 14, 134, 138

line number The numerical order in which Boeing builds aircraft. Each airplane program has its own set of line numbers, and each new airplane built receives a line number in numerical order. For example, if the 737 line has built 100 airplanes previously, the next airplane would receive line number 101. 101

manufacturing day A day during the normal Monday through Friday work week (excluding holidays) that manufacturing operations occur. These days are number consecutively in increasing order. Any standard work day is a manufacturing day and will receive an M day number. Work executed on a non-manufacturing day is recorded with the M day number associated with the most recent M day (example: work executed during overtime on a Saturday would be annotated with the preceding Friday's M day number). 117, 118

material issue note A printed document that notifies the warehouse to produce and deliver a kit to the closet fabrication line. This document is printed on paper and delivered to the warehouse management team by the closet fabrication line industrial engineer. 94, 106

mechanic A front-line manufacturing worker that executes the day-to-day work for parts fabrication and aircraft assembly. Mechanics fill a wide variety of roles, from installing parts to painting aircraft. 35, 47–50, 57–59, 68, 69, 75, 76, 87, 91, 117, 121, 123

non-conformance A defect or improperly completed step in the fabrication process. A non-conformance may require re-work, additional parts, approved changes from Boeing's engineers, and/or inspection from quality assurance personnel. 30

picker Individuals that work in a Boeing warehouse and fulfill orders by locating items in the warehouse and adding them to an order. This process, known as picking, requires the picker to move throughout the warehouse, locate the needed items, and retrieve the items from the warehouse bins. 48, 99, 100

sweep and sand This process cleans the closet's exterior panels and sidewalls of dust, sands the panels smooth to remove excess epoxy, and prepares the panels for the application of decorative laminate. The final step in this process is the application of decorative laminate to the surface that require it. 14, 30, 132, 136

tab and slot The initial closet assembly process that fits exterior panels together and applies initial epoxy to panel joints. This process varies depending on how the age of the closet model. Older closet models may require additional joining work following the tab and slot process, whereas newer closet models have their sidewalls joined during this stage. 14, 30, 133, 137

takt The pace at which the factory must produce items to meet customer demand. This time governs the pace at which the factory, and its subordinate elements, must operate. Takt time is measured in units of time/item (days/airplane, for example). A takt time of 5 days/airplane implies that the factory must produce an airplane every five days to meet customer demand. 28, 37, 38

Appendix A

Current State Analysis Plots

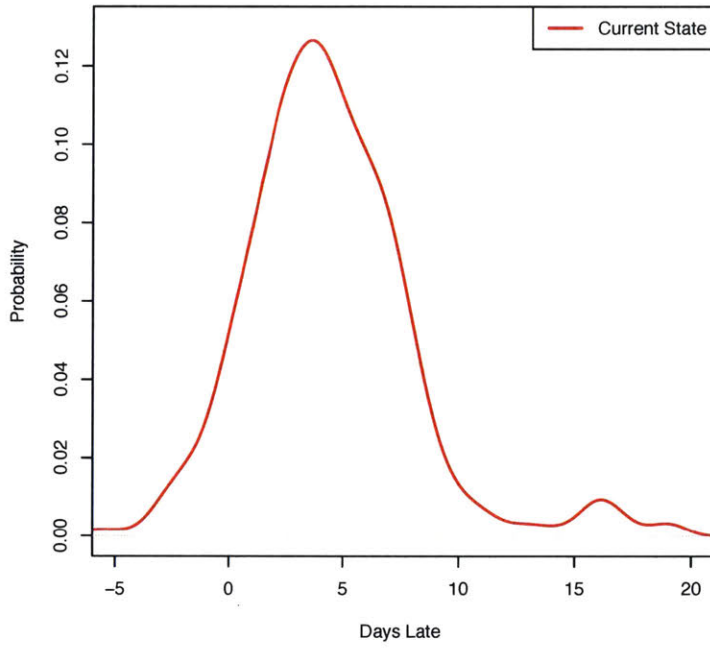


Figure A-1: Current state of late deliveries, all airplane programs

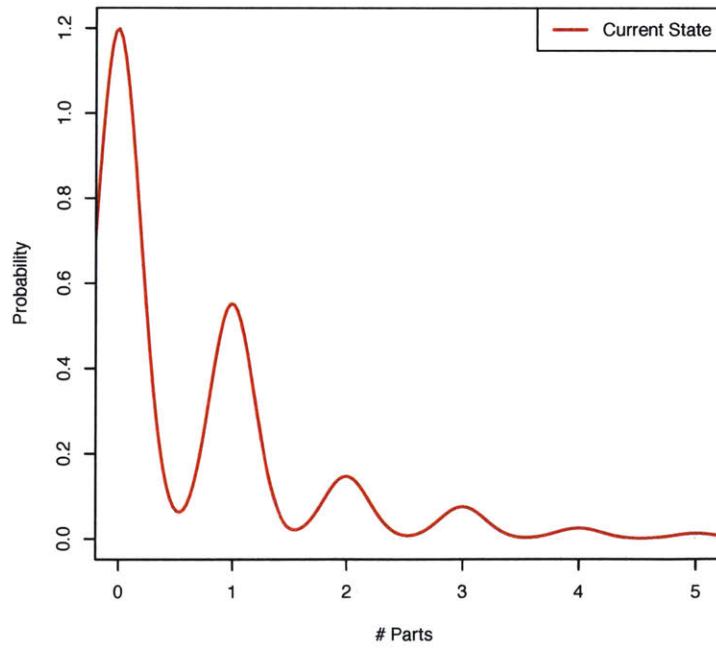


Figure A-2: Current state of stocked out parts, all airplane programs

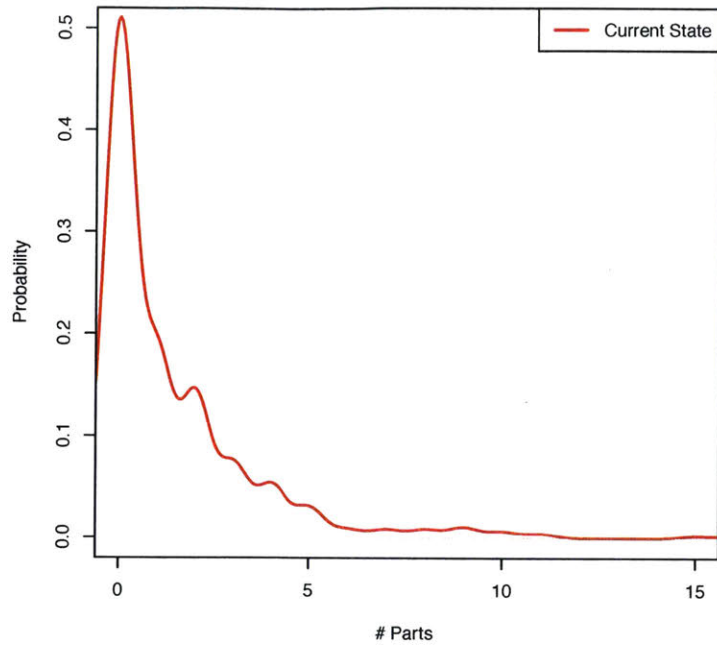


Figure A-3: Current state of missing parts, all airplane programs

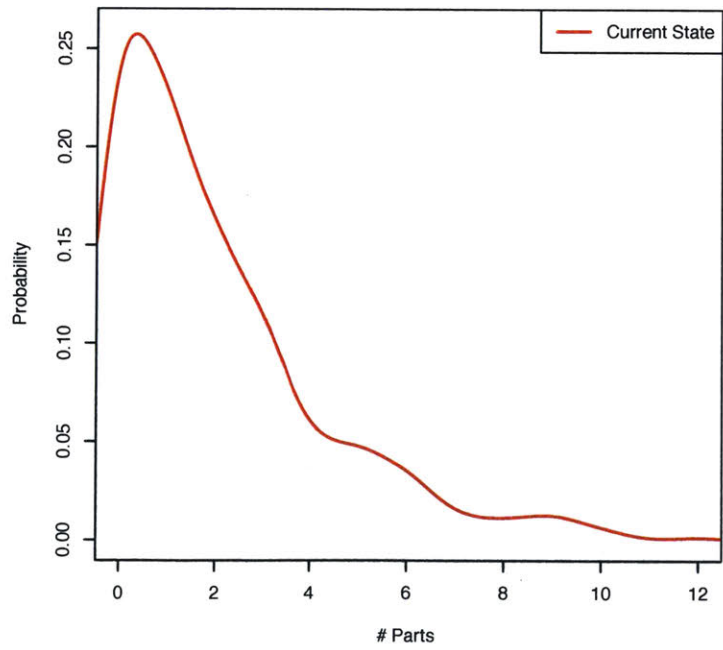


Figure A-4: Current state of total missing parts, all airplane programs

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix B

Distribution Fitting Plots

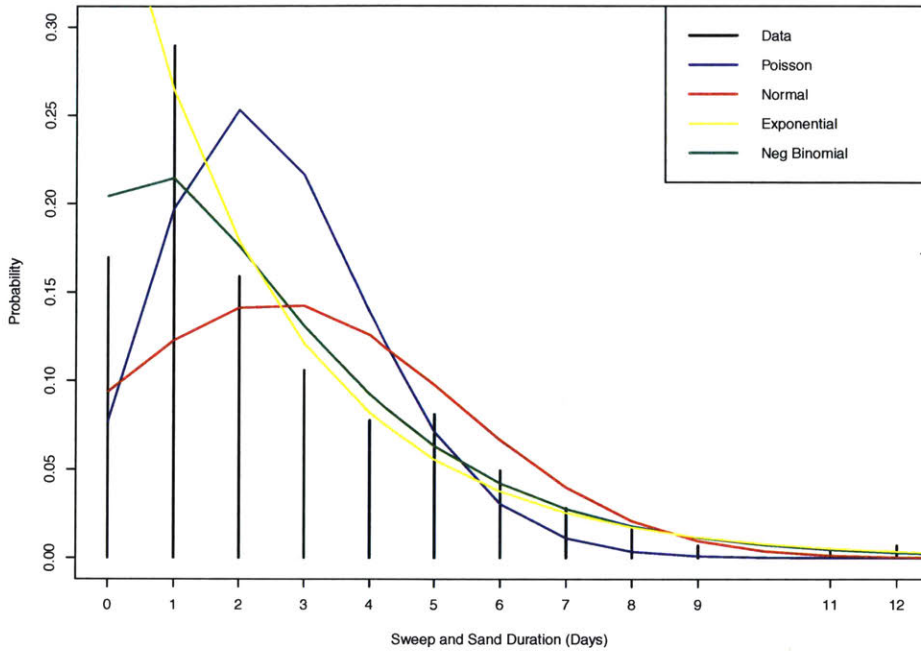


Figure B-1: Probability distributions for Program A sweep and sand process

Table B.1: Distribution parameters for Program A sweep and sand process

Distribution	Parameter	Value
Poisson	Rate	2.57
Normal	Mean	2.57
Normal	Std Dev	2.77
Exponential	Rate	1.78
Negative Binomial	Size	2.57
Negative Binomial	Mean	0.39

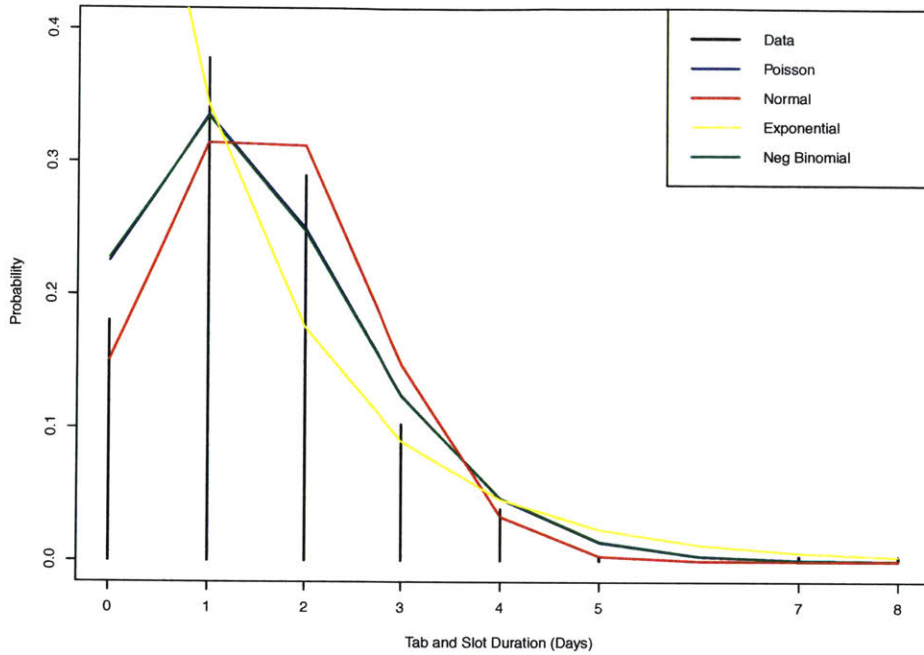


Figure B-2: Probability distributions for Program A tab and slot process

Table B.2: Distribution parameters for Program A tab and slot process

Distribution	Parameter	Value
Poisson	Rate	1.49
Normal	Mean	1.49
Normal	Std Dev	1.16
Exponential	Rate	804857.01
Negative Binomial	Size	1.49
Negative Binomial	Mean	0.67

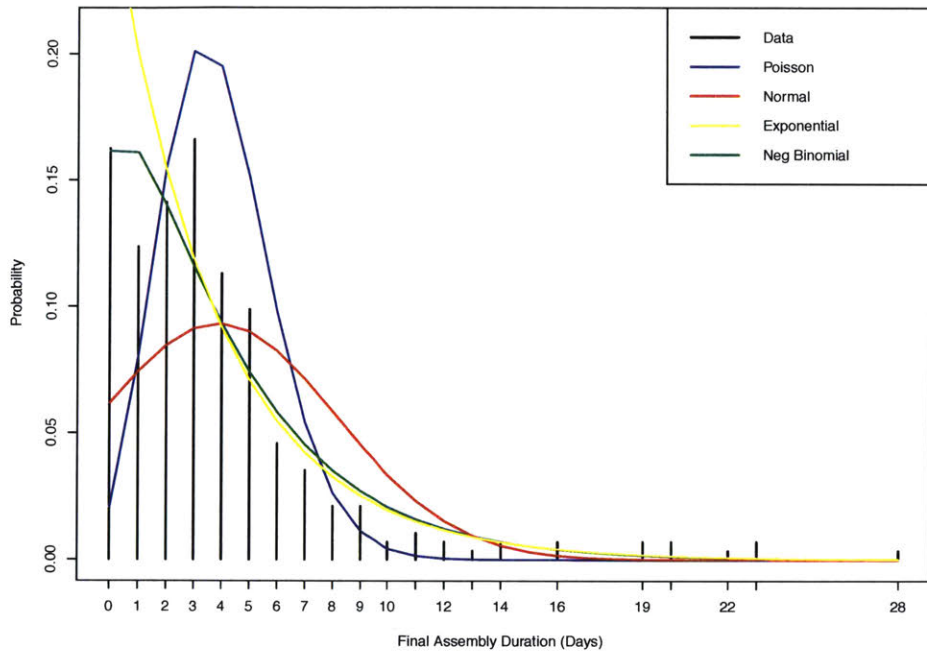


Figure B-3: Probability distributions for Program A final assembly process

Table B.3: Distribution parameters for Program A final assembly process

Distribution	Parameter	Value
Poisson	Rate	3.88
Normal	Mean	3.88
Normal	Std Dev	4.27
Exponential	Rate	1.34
Negative Binomial	Size	3.88
Negative Binomial	Mean	0.26

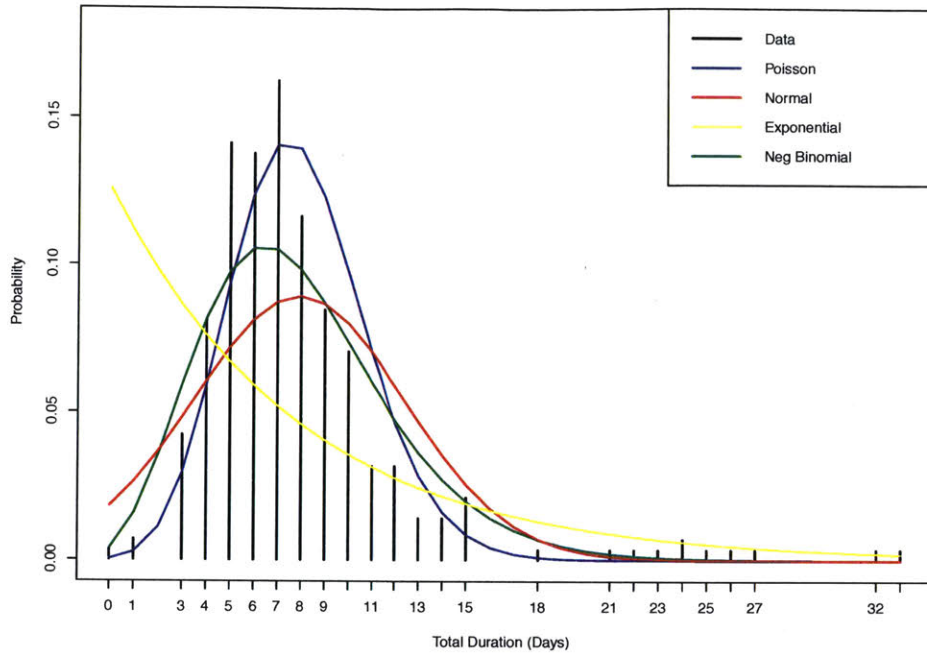


Figure B-4: Probability distributions for Program A fabrication process total duration

Table B.4: Distribution parameters for Program A total duration

Distribution	Parameter	Value
Poisson	Rate	7.94
Normal	Mean	7.94
Normal	Std Dev	4.46
Exponential	Rate	8.05
Negative Binomial	Size	7.94
Negative Binomial	Mean	0.13

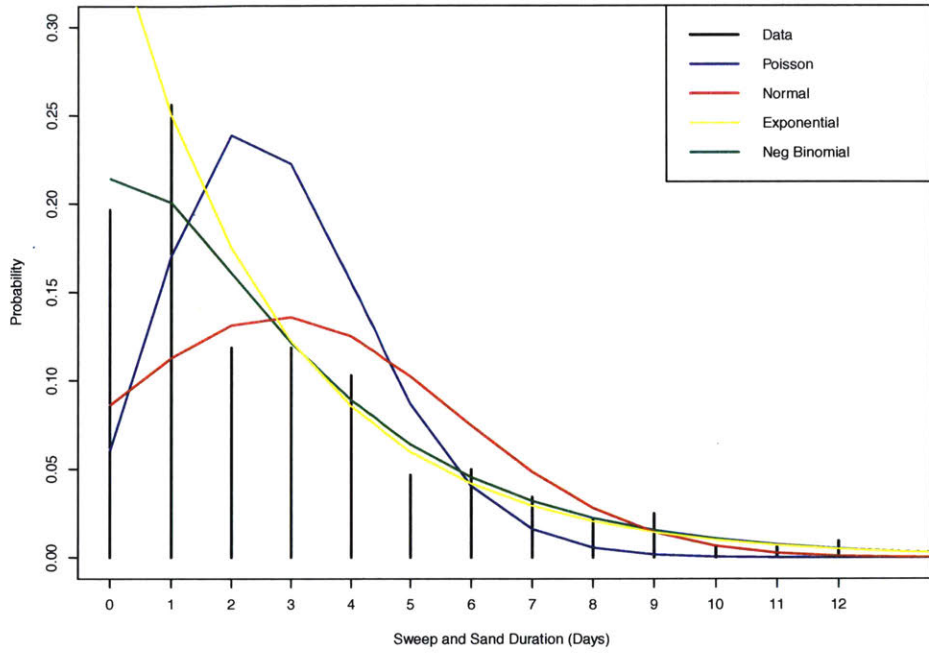


Figure B-5: Probability distributions for Program B sweep and sand process

Table B.5: Distribution parameters for Program B sweep and sand process

Distribution	Parameter	Value
Poisson	Rate	2.80
Normal	Mean	2.80
Normal	Std Dev	2.93
Exponential	Rate	1.41
Negative Binomial	Size	2.80
Negative Binomial	Mean	0.36

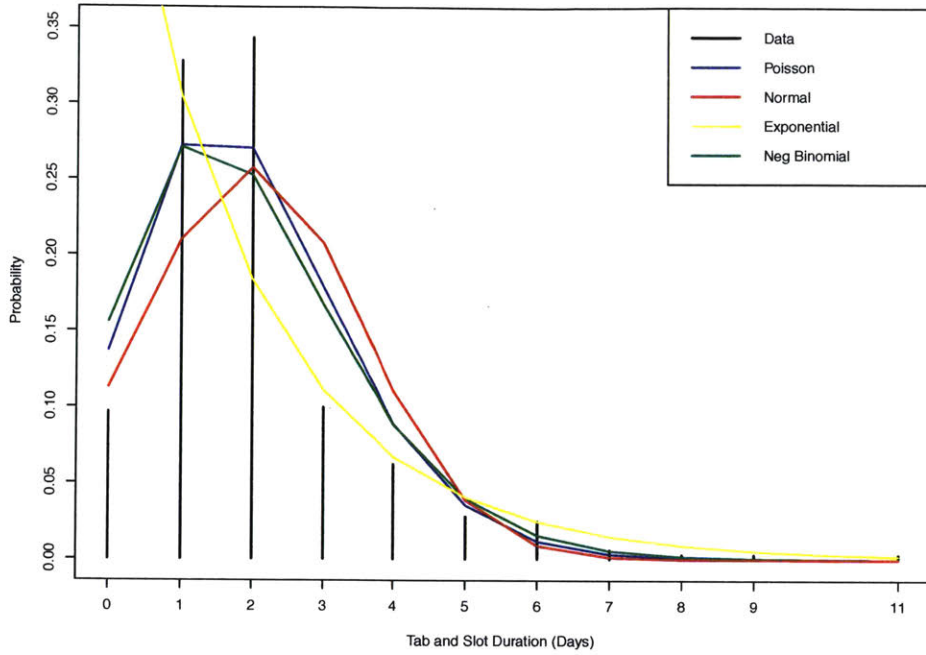


Figure B-6: Probability distributions for Program B tab and slot process

Table B.6: Distribution parameters for Program B tab and slot process

Distribution	Parameter	Value
Poisson	Rate	1.99
Normal	Mean	1.99
Normal	Std Dev	1.55
Exponential	Rate	14.03
Negative Binomial	Size	1.99
Negative Binomial	Mean	0.50

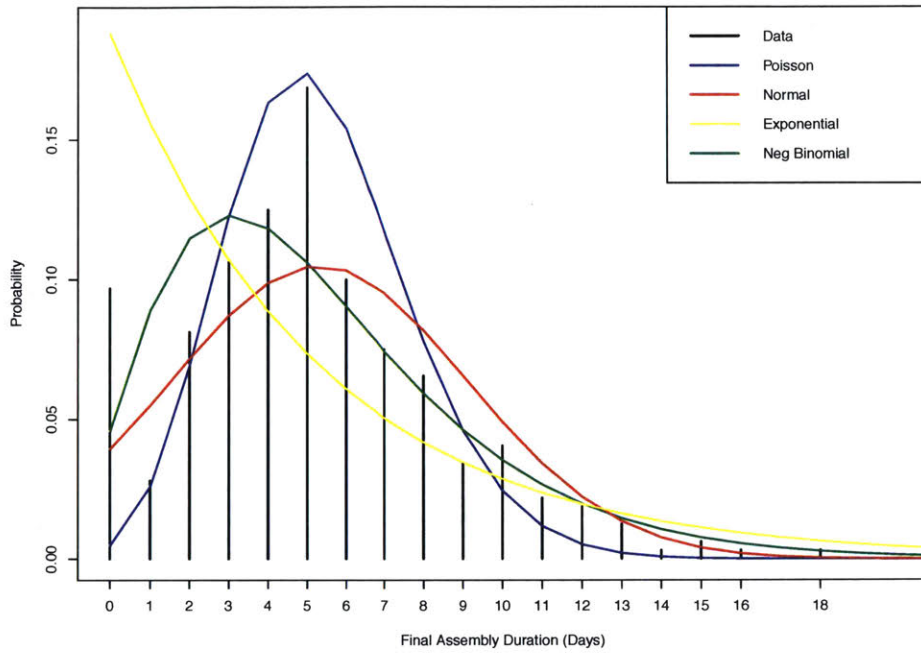


Figure B-7: Probability distributions for Program B final assembly process

Table B.7: Distribution parameters for Program B final assembly process

Distribution	Parameter	Value
Poisson	Rate	5.32
Normal	Mean	5.32
Normal	Std Dev	3.80
Exponential	Rate	3.06
Negative Binomial	Size	5.32
Negative Binomial	Mean	0.19

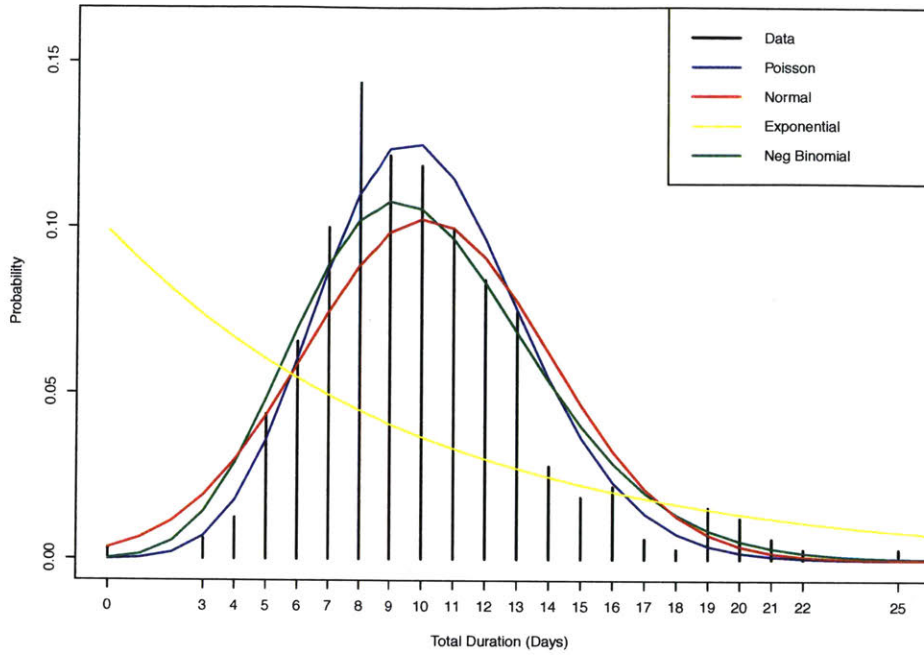


Figure B-8: Probability distributions for Program B fabrication process total duration

Table B.8: Distribution parameters for Program B total duration process

Distribution	Parameter	Value
Poisson	Rate	10.10
Normal	Mean	10.10
Normal	Std Dev	3.89
Exponential	Rate	25.06
Negative Binomial	Size	10.10
Negative Binomial	Mean	0.10

THIS PAGE INTENTIONALLY LEFT BLANK

Bibliography

- [1] Nabil Adam and Julius Surkis. A Comparison of Capacity Planning Techniques in a Job Shop Control System. *Management Science*, 23(9):1011–1015, 1977.
- [2] Albert D Baker. A survey of factory control algorithms that can be implemented in a multi-agent heterarchy: Dispatching, scheduling, and pull. *Journal of Manufacturing Systems*, 17(4):297 – 320, 1998.
- [3] C. T. Baker and B. P. Dzielinski. Simulation of a Simplified Job Shop. *Management Science*, 6(3):311–323, 1960.
- [4] Deborah Benson. Simulation Modeling and Optimization using ProModel. *Proceedings of the 1997 Winter Simulation Conference*, page iii, 2002.
- [5] Jos A. C. Bokhorst and Jannes Slomp. Lean Production Control at a High-Variety, Low-Volume Parts Manufacturer. *Interfaces*, 40(4):303–312, 2010.
- [6] Michael H. Bulkin, John L. Colley, and Harry W. Steinhoff. Load Forecasting, Priority Sequencing, and Simulation in a Job Shop Control System. *Management Science*, 13(2):B29–B51, 1966.
- [7] Donald C. Carroll. *Heuristic sequencing of single and multiple component jobs*. PhD Thesis, Massachusetts Institute of Technology, 1965.
- [8] Earl LeGrande. The Development of a Factory Simulation System Using Actual Operating Data. *Management Technology*, 3(1):1–19, 1963.
- [9] S. S. Panwalkar and Wafik Iskander. A Survey of Scheduling Rules. *Operations Research*, 25(1):45–61, 1977.
- [10] Stephen Trimble. ANALYSIS: Latest 787 line remake adds AGVs and 2h work kits. *Flight Global*, September 2016.
- [11] Airline Suppliers Website. Photo of a typical commercial airplane closet. <https://www.airline-suppliers.com/wp-content/uploads/2016/07/AIM-Alt-5-1.png>. Accessed: 2018-01-30.