# Optimizing Large-Volume Scheduling for Cost Avoidance

By

Tamara Belkina

B.S. Computer Science, The Pennsylvania State University (2008)

Submitted to the MIT Sloan School of Management and the Institute for Data, Systems, and Society in partial fulfillment of the requirements for the degrees of

Master of Business Administration

and

Master of Science in Engineering Systems

in conjunction with the Leaders for Global Operations Program at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2016



Author..... Signature redacted ...
MIT Sloan School of Management, Engineering Systems Division
May 6, 2016

Certified by..... Signature redacted .....
Daniel Whitney, Thesis Supervisor
Senior Research Scientist, Emiritus

Certified by..... Signature redacted .....
Karen Zheng, Thesis Supervisor
Assistant Professor, Operations Management

Accepted by..... Signature redacted .....
John N. Tsitsiklis
Clarence J. Lebel Professor of Electrical Engineering
IDSS Graduate Officer

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

# Optimizing Large-Volume Scheduling for Cost Avoidance

By

Tamara Belkina

Submitted to the MIT Sloan School of Management and the MIT Engineering Systems Division
on May 6, 2016 in partial fulfillment of the requirements for the degrees of
Master of Business Administration and Master of Science in Engineering Systems

## Abstract

This dissertation presents the results of developing optimization algorithms for use in operational scheduling of airplane stalls and paint hangars at the Boeing Company's Everett Delivery Center. With the increasing number of orders, more airplanes are coming out of the Everett Factory and into the flightline for painting, fueling, and other pre-delivery testing activities. While Boeing's existing infrastructure is still well able to support this increasing scale of operations, some of the existing manual scheduling processes become more time consuming and sprout inefficiencies. This existing scheduling process was mapped and analyzed, and an Excel VBA tool was developed in collaboration with Boeing's Applied Math group to provide visibility into cost avoidance opportunities for the Everett Delivery Center. As a result of this work, up to 35% of paint hangar costs have been identified as potentially avoidable.

Thesis Supervisor: Daniel Whitney
Title: Senior Research Scientist, Emeritus

Thesis Supervisor: Karen Zheng
Title: Assistant Professor of Operations Management

# Acknowledgements

I would like to thank the MIT Leaders for Global Operations program and The Boeing Company for their support of this dissertation. A huge thank you to Michael Catalano, Allison Sullivan, Julie Chun, and the rest of the Everett Delivery Center team for their continuous help and support throughout my internship, as well as for making me feel welcome at Boeing.

I would also like to thank my fearless thesis advisers, Daniel Whitney and Karen Zheng, who were always willing to help and point me in the right direction.

A big thank you to all my LGO classmates who have supported me and helped me learn. Your friendship and principled leadership made these past two years truly wonderful.

I am extremely grateful for the constant love and support of my family. My parents Grigory and Alla as well as my sister Ekaterina have always encouraged me in all of my endeavors, academic and otherwise. Joe Cockriel, my husband and best friend, has truly made my MIT experience possible, from driving me to my GMAT exam when the NYC subway unexpectedly shut down, to reviewing my application essays the night before they were due, to supporting and tolerating my late night thesis writing sessions. Lastly, I would like to thank my dog Chewbacca, who has tenaciously napped by my side throughout my thesis writing process.

*This page has been intentionally left blank.*

# Contents

# List of Figures

*This page has been intentionally left blank.*

# List of Tables

*This page has been intentionally left blank.*

# Chapter 1

# Introduction

As optimization technology becomes more and more accessible with advances in software and computing power, any corporation that handles large-volume scheduling can stand to benefit from utilizing optimization tools. There are numerous benefits. With the power of optimization, business can evaluate complex decisions that involve limited resources. A much wider set of options and solutions can be discovered and automatically evaluated while planning staff can focus on more challenging problems. [1]

## 1.1 Purpose of Study

The goal of this research is to explore and evaluate possible benefits of applying optimization methodologies to scheduling activities at The Boeing Company's Everett Delivery Center (EDC). The research focused on minimizing costs for two separate scheduling processes at the EDC: paint hangar scheduling and stall move scheduling. Both of the two existing scheduling processes are currently manual. Optimization algorithms were developed to examine potential cost savings that could be achieved if the scheduling processes were automated.

## 1.2 Approach

The research first focused on identifying, mapping out, and evaluating the existing paint and stall scheduling processes at the Everett Delivery Center that could benefit from optimization methodologies to derive a scheduling solution.

The first identified process is paint hangar scheduling. Currently, there is a manual process that assigns each airplane to an off-site or on-site paint hangar, which each location carrying various contractual costs. Factors other than cost are taken into account, such as customer preferences. This research developed an algorithm to identify potential cost savings if airplanes were assigned to paint hangars, based on lowest cost only.

The second identified process is stall move scheduling. The current process is manual, extremely complex, and time-consuming. A full-time Boeing employee assigns airplanes to different stalls as they go through the EDC processes. Each stall move carries a financial cost for Boeing. This research aimed to develop an algorithm that uses optimization techniques to minimize the total required stall moves, and thus costs, for Boeing.

Once the processes were identified, optimization algorithms were developed to conduct a pilot study and the results from the pilot study were analyzed. Ultimately, this research concluded in recommendations to The Boeing Company for future optimization work of each scheduling process that was involved.

## 1.3 Dissertation Roadmap

Chapter Two provides necessary background of the Everett Delivery Center and the scheduling processes that are relevant for this research. A thorough review of existing manual processes provide context for the rest of the research.

Chapter Three focuses on reviewing relevant work in the field both in the airline and in other similar industries.

Chapter Four discusses the approach for technology development for the pilot optimization study, while Chapters Five and Six detail the algorithm development for each of the scheduling processes involved.

Finally, Chapter Seven outlines recommendations for each of the scheduling processes and provides conclusions to the research.

*This page has been intentionally left blank.*

# Chapter 2

# Background

## 2.1 The Boeing Company's Everett Delivery Center (EDC)

Boeing Commercial Airplanes (BCA) is a division of The Boeing Company that designs and manufactures commercial jetliners. BCA currently produces five product lines: 737, 747, 767, 777, and the 787 Dreamliner. The smallest of the five, the single-aisle 737, is manufactured in the Renton site near Seattle, Washington and some 787s get assembled in the new South Carolina facility. All other jetliners are assembled at the world's largest manufacturing building, the factory in Everett, Washington [2]. Once a newly manufactured airplane leaves the Everett factory, it is transported next door to the Everett Delivery Center (EDC). The EDC delivered more than 200 airplanes in 2015[3]. Each airplane can take over a month to go through all of the EDC steps and there are usually between twenty and thirty airplanes in the EDC at one time.

At the Everett Delivery Center, the airplane will undergo four phases in four discrete location types:

1. Painting in a paint hangar
2. Fueling in a fuel dock stall
3. Final inspections & flight tests in a production stall

4. Delivery in a delivery stall

Various schedules influence how each airplane flows through these locations.

## 2.2 Desired Flow Through the EDC

Once an airplane is assembled in the factory, it will move into the Everett Delivery Center property, which is commonly referred to as the flightline. In an ideal world, once the airplane rolls out of the factory it would go directly to a paint hangar, then it would proceed into a fueling stall, then to a production stall, and finally to a delivery stall prior to departing from the adjacent Paine Field Airport runway. This would result in a grand total of four moves while in the Everett Delivery Center flow. Each move involves a specialized crew and equipment, which physically moves the airplane from one stall to another. Figure 1 is a sample visual representation of this ideal flow for an airplane.

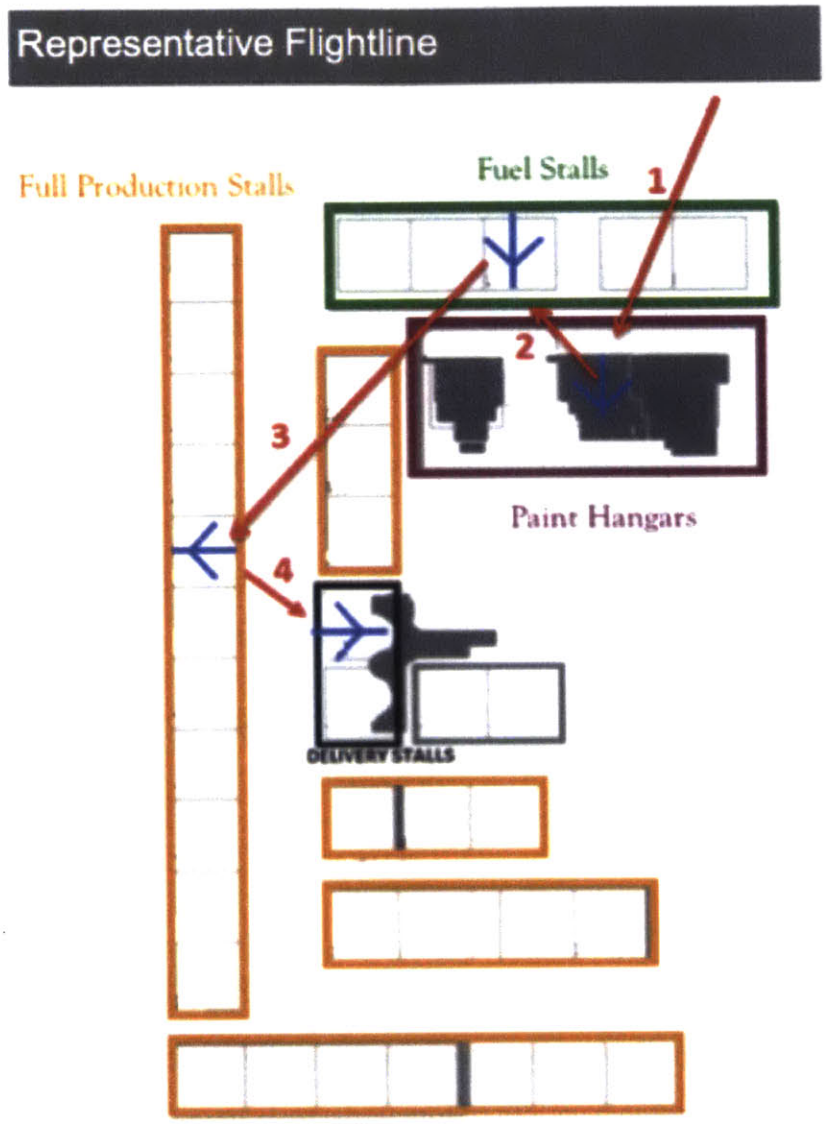


Figure 1: Desired Flow Through the Everett Delivery Center

## 2.2.1 Paint

Each customer has their own paint scheme (livery) for how they want the airplane to look. These paint schemes, or liveries, range from simple to elaborate, and some are borderline artwork. The painting phase can be completed either in a highly specialized enclosed on-site

paint hangar, or in an off-site paint hangar. Boeing paint schedulers are in charge of manually creating paint schedules and assigning a paint hangar location for each airplane.

Since every customer has unique design and requirements, the paint process and required time of the paint job can have a lot of variation. For example, the mostly composite 787 Dreamliners come out of the factory with a shiny coat of paint already on, whereas mostly metal airplanes come out with a green anti-corrosive coating. The paint process differs for these two types of base layers.

If a paint scheme is the first of its kind to be done in that paint hangar, more time will be allocated to account for any unforeseen difficulties. If any special non-standard paints, such as metallic finish, or color fading are required, this could also add time. The more elaborate the design and the bigger the airplane, the more time it takes to paint.

With all of these variations, a typical paint job could have variations by as much as two to four days.

### 2.2.2 Fuel

Fueling has to be completed in a fuel dock. During this step, the airplane's fuel tanks get filled for the first time and then undergo a variety of functional tests to ensure all is balanced and leak-proof. Fueling time varies depending on the airplane program type.

### 2.2.3 Final Inspections & Flight Buy-off

In this step the airplane utilizes a production stall, where shake and functional tests are performed and engines are run. There is a large list of tests prescribed by the Federal Aviation Administration (FAA) that need to be performed before an airplane is deemed airworthy. Customers will also walk through the plane and complete their own inspection of the airplane. At this point in the process the plane is flight ready and will undergo two flight tests. During this

time the airplane is flown for the first time, first receiving airworthiness acceptance by Boeing and the FAA. Once that is complete, the airline customer will conduct the second flight test. The aircraft is then ready for delivery.

The final inspection & testing phase duration varies depending on the customer, the program, and the specific statement of work associated with each airplane. EDC plans the scheduling of the final inspection & testing phase well in advance due to the large variation in cycle time. This can be done because each airplane's customer, program, and statement of work are known months beforehand.

### 2.2.4 Delivery

The airplane is then moved to a delivery stall. The customer sometimes makes the delivery into a fun event, hosting a special lunch or dinner celebration. Standard airport security procedures are followed, and TSA personnel are present as the customer's pilots and passengers board the aircraft. When the cabin door is closed, the plane taxies to Paine field for flyaway.

## 2.3 Process Complexity

While the process described so far is what is desirable by design, unfortunately most of the time there is a lot more complexity involved. There are several process complications that can happen along the way and affect the ideal flow, such as:

1. Capacity Constraints
2. Build or performance issues
3. Customer requested delays

Each of these complications can drive additional needs for stall capacity.

Because the EDC handles a large volume of airplanes at any given time while operating under capacity constraints and dependencies at each phase, all of the airplanes are assigned their stalls far in advance to ensure the most efficient flow. Therefore, if any of the above complications occur on a single airplane and the assignments have to be readjusted, this can set off a domino effect of additional moves and delays for multiple other airplanes. As a result, the stall schedule has to be continuously updated as these issues come up in order to identify and eliminate any ensuing impact.

### 2.3.1 Capacity Constraints

All of the stalls at the EDC are physical resources that are finite. The ideal flow scenario makes an assumption that there is always capacity to accommodate each airplane in all the steps. Realistically, that is often not the case, especially with paint hangars. In the ideal flow scenario an airplane will go straight to a paint hangar upon entering the EDC workflow. Frequently all the paint hangars are already occupied by airplanes, which results in adjustments to the flow and ultimately extra stall moves. The on-site average monthly utilization can get rather high, leading to the need for off-site paint hangars.

### 2.3.2 Build and Performance Issues

Throughout the EDC lifespan of an airplane there are several customer inspections, where the customer comes on site and examines the plane, documenting anything they would like fixed (the "pick-ups"). The resulting rework from these pick-ups has to be incorporated into the EDC flow.

A pick-up could be a scratch or dirt on a passenger seat. This would lead to the seat having to be cleaned, fixed, or even replaced. A more involved pick-up could be dissatisfaction with the

paint job of the airplane. Fixing this type of pick-up could add an extra day for a paint touch-up, or in the worst case scenario it would involve having to re-paint the entire airplane.

Furthermore, more issues could be noticed during test flights. Those are documented as "squawks" and also result in rework. A squawk usually involves the need for a simple cockpit interface or software adjustment. It could also involve a more serious flaw in the aircraft, such as any equipment not functioning as expected during the flight, but this is rare.

Ultimately all of the squawks and pick-ups are addressed, and the airplane is delivered in great condition to the customer. However, due to unexpected and unpredictable nature of pick-ups and squawks, they can have a major impact not only on the schedule of that airplane, but also on the other airplanes that are in the EDC workflow at the same time.

### 2.3.3 Customer Requested Delays

Sometimes the customer requests the delivery date of their airplane to be moved further in the calendar due to various business reasons. This type of request will naturally always be accommodated. While sometimes customer-requested delays provide Boeing with more flexibility, other times they create a domino effect of scheduling changes. Other airplanes may have been scheduled for that stall, in which case the stall assignment schedule will have to be modified. If the requested delay is for a longer period of time, arrangements will be made for either on-site or off-site storage. Parking stalls at the nearby Paine Airfield are often utilized for off-site storage because of location convenience.

### 2.3.4 Realistic Flow

Section 1.2 gave an overview of the ideal flow through the Everett Delivery Center. Due to capacity constraints, potential build and performance issues, and customer-requested delays

the realistic flow is more complicated in its nature. Due to capacity restrictions, most airplanes deviate from the ideal flow and end up with a significantly more complicated path through EDC. Figure 2 displays a histogram of the number of airplane moves based on 2015 data.

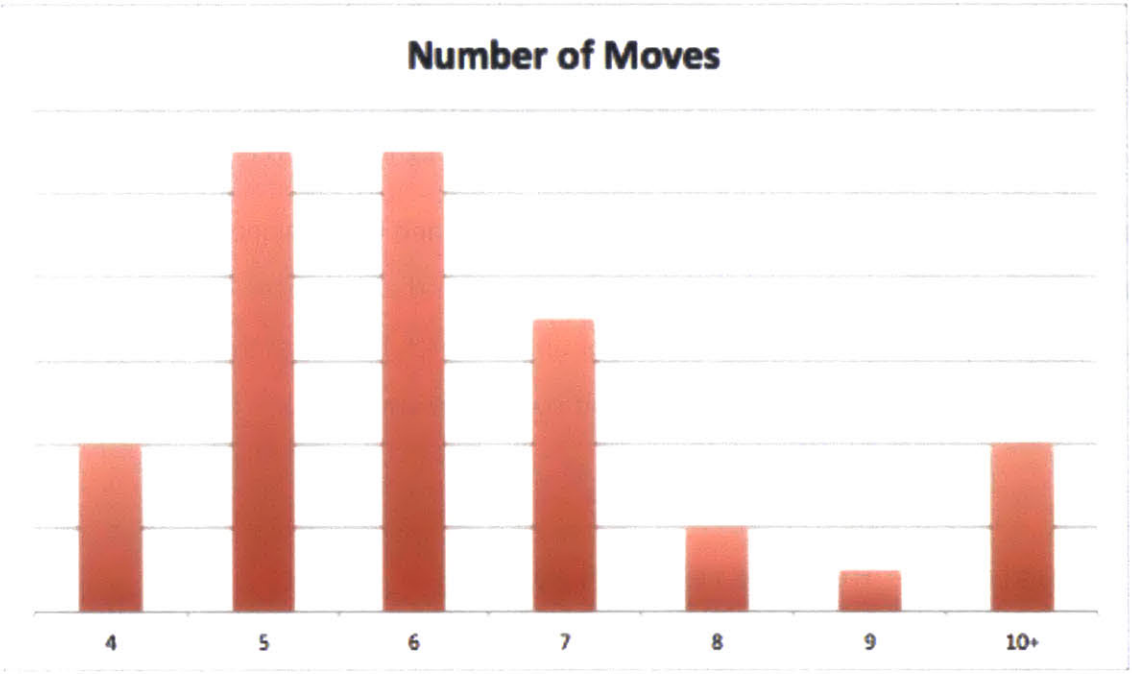


Figure 2: Number of Airplanes Stall Moves

Figure 3 shows a typical realistic path through EDC. In this example, the aircraft could not go directly to a paint hangar since all of them were already occupied. It also could not go yet to its home production stall as it was also occupied. So its path was as follows:

1. Temporary production stall
2. Home production stall
3. Paint hangar
4. Fuel stall
5. Home production stall
6. Delivery stall

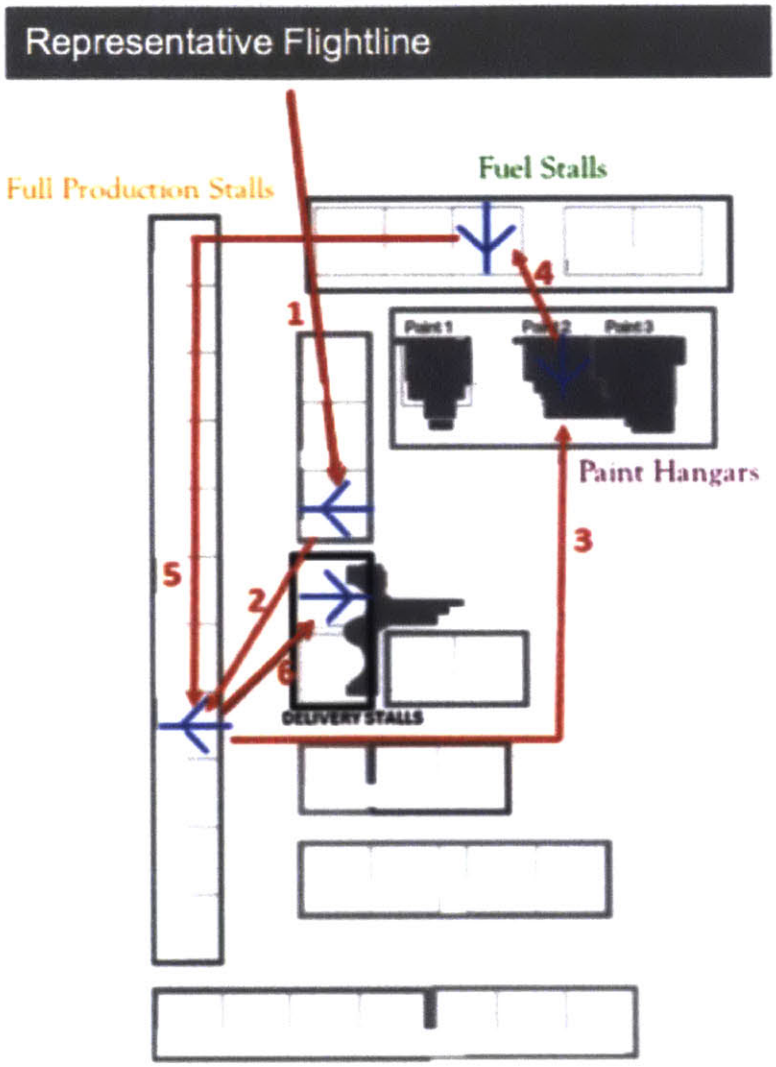


Figure 3: Typical Realistic Path Through the Everett Delivery Center

## 2.4 Scheduling Complexity

The existing paint and stall scheduling processes at the EDC are mostly manual and quite labor-intensive. The more airplanes are in the system, the more complex and time intensive the process becomes. Table 2 shows the rapidly increasing number of Boeing's wide-body airplane deliveries over the past six years. [3] This rapid increase can be largely attributed to the introduction of the new 787 Dreamliner model. While the increasing number of deliveries is

excellent for business, it also complicates the paint hangar and stall scheduling processes. Manual scheduling of stall moves is a lot more difficult now than six years ago, mainly due to the introduction of the 787 program as well due to an overall increase of airplanes in the EDC system at a given time.

Table 1: Boeing Wide-Body Airplane Deliveries 2010-2015

| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|
| 747 | 0 | 9 | 31 | 24 | 19 | 18 |
| 767 | 12 | 20 | 26 | 21 | 6 | 16 |
| 777 | 74 | 73 | 83 | 98 | 99 | 98 |
| 787 | - | 3 | 46 | 65 | 114 | 135 |
| Total | 86 | 105 | 186 | 208 | 238 | 267 |

### 2.4.1 Paint Scheduling

Boeing owns and operates multiple paint hangars in Everett. Due to recent increases in the number of deliveries, Boeing partners with several vendors who are able to paint airplanes at their off-site locations to supplement the on-site paint hangar capacity. There is currently an EDC Team that is dedicated to managing all paint activities, including scheduling. The existing process entails manually creating a visual schedule for an entire year for all the paint hangars and airplanes. Paint hangars assignments to airplanes take into consideration multiple variables including delivery dates, customer preferences, and the expertise of each paint hangar with the specific paint scheme that is involved.

Painting costs between paint hangars can vary depending on the paint scheme, the airplane program, equipment setup, and labor costs. Additionally, there are penalties in place for underusing or overusing paint hangars.

### 2.4.2 Stall Scheduling

Stall assignments and scheduling all of the airplane moves at the EDC is currently a full-time job. The employee responsible for this task creates an excel schedule of where each airplane in the system should be located at each stage in the process for a time period of several months into the future. The schedule for the upcoming two weeks tends to be more detailed while the schedule for a month out blocks out the approximate future stall needs. Figure 4 illustrates the process involved. The employee must take multiple schedules from several different groups as inputs before a schedule can be created. The inputs can include:

1. The paint schedule dictates the paint hangar and dates assigned to each airplane.
2. Crew cycling dictates which crew is assigned to each airplane on each day.
3. Factory roll out schedule sets the schedule for when each airplane will be rolling out of the factory and starting its flow at the EDC.

With these three schedules the employee has all the requirements to create the stall schedule. The employee uses their expertise to manually organize and optimize the schedule with the intention to minimize overall stall moves and maximize efficiency in the system. The schedule is a living document, as any changes in any of the input schedules will trigger the reorganization of the stall schedule. Additionally the employee may receive emergent requests to make changes, which will also trigger re-optimization of the schedule.

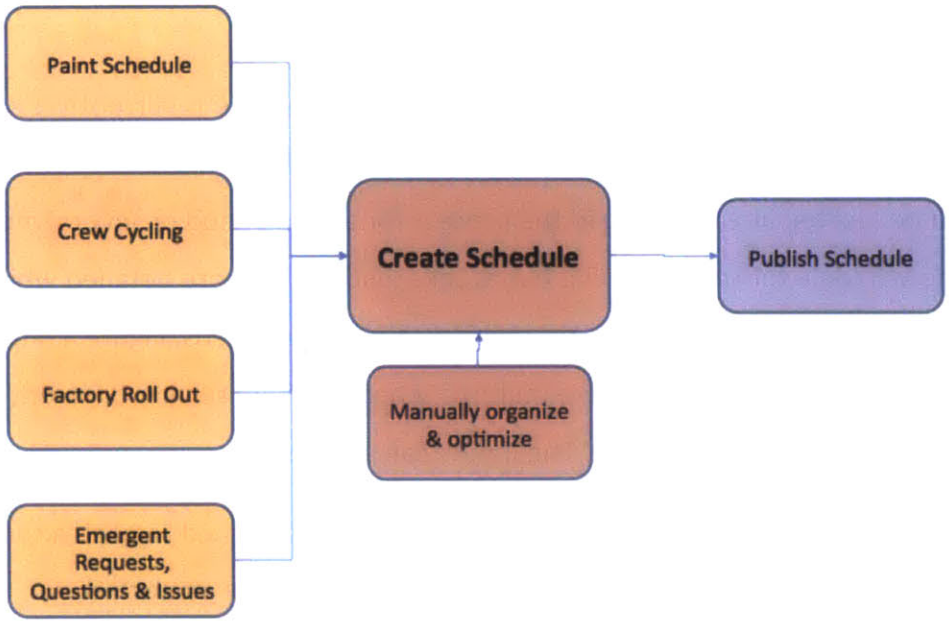


Figure 4: Existing Stall Move Scheduling Process

## 2.5 Chapter Summary

The Boeing Company's Everett Delivery Center (EDC) oversees the painting, fueling, final inspection & tests, as well as delivery of wide-body jetliners. Ideally an airplane will move only four times through the EDC in order to complete these process steps. In reality, capacity restrictions as well as complications cause the actual number of moves to be higher than four. With a rapidly growing number of yearly deliveries, the current manual paint and stall scheduling processes become more burdensome and complicated for the manual scheduler.

# Chapter 3

# Literature Review

Efficiency in production scheduling is far from new. The topic of efficiency received a lot of attention during World War I when Henry Laurence Gantt developed his famous Gantt Charts in order to improve wartime production scheduling. [4] Two decades later, as a result of World War II, George Dantzig was the first person to develop and use linear programming to solve logistics problems. There has been an incredible amount of research on the topic since, especially as computer technology becomes more powerful and accessible. Today, efficient scheduling has gained significant operational importance in both service and manufacturing industries. [5] This chapter will review a small subset of available research, specifically as it relates to the topic of this study.

## 3.1 Optimization and Mathematical Programming as a Tool in Aircraft Scheduling Problems

Several previous studies have addressed a similar aircraft scheduling problem. Martin, Jones, and Keskinocak [6] successfully applied linear optimization using a CPLEX-based algorithm to the Fractional Aircraft Operator (FAO) industry in 2003. Fractional aircraft operators became a popular cost-efficient substitute to corporations owning and operating their own private business jets. FAO companies own and operate a large fleet of private business jets and let

multiple corporations and private firms use these jets as needed. This model is cheaper for corporations and private firms because they no longer need to own and maintain the jets themselves and still get the full benefit of using private business jets.

The FAO companies face a challenge of managing and scheduling large fleets of various aircraft types and sizes. Additionally, they must meet customer requests for aircraft on short notice, while accommodating each aircraft's maintenance schedule and FAA regulations regarding crew fatigue. Similar to the EDC problem, the manual scheduling of flights for an optimal scenario becomes nearly impossible given the complexity of rules, constraints, and options. Additionally, since new flight requests can come at any moment, there is a need to dynamically update and optimize the schedule.

Martin, Jones, and Keskinocak developed an algorithm that was able to automatically optimize airplane schedules with the goal of minimizing operating costs for the FAO. Similar to the EDC problem, the goal of this endeavor was to minimize unnecessary movement of airplanes and achieve cost savings. In both cases, there are very specific business constraints: meeting customer deliveries on time, performing necessary maintenance activities, and accommodating crew scheduling.

In addition to the optimization algorithm, the tool was able to handle the entire scheduling business process of an FAO company, including storing customer contracts, maintenance schedules, and FAA regulations regarding crew fatigue requirements. The tool lets planning staff run scenarios and instantly compare multiple scenarios for profitability and cost-effectiveness.

As a result, one company that purchased and used this software was able to reduce unnecessary positioning flights by 18.7% and achieved savings of $4.4M in one year. [6]

A different study by Indika and Shier [7] used a mixed integer quadratic programming model to solve a scheduling problem for facilities that do modifications and maintenance on aircraft. These facilities have multiple hangars, with each hangar having multiple bays where jobs can be scheduled. The goal of the optimization is to maximize the utilization of the overall facility as well as provide increased capacity for any future jobs.

While these solutions are not an exact fit for the EDC scheduling problem, they certainly demonstrate the benefit of using automated optimization for aircraft scheduling. These existing solutions could not be applied to the EDC problem directly since they are highly customized to their particular uses and require licensing, which was beyond the budget of this research.

## 3.2 The Application of Optimization and Linear Programming in the Airline Industry

There are multiple applications of linear programming and optimization in the broader airline industry. Though airline operations and aircraft manufacturing are quite different, both have operational problems that involve the movement of aircraft. Therefore, insight can be gained from examining these applications in the airline industry. There has been a plethora of emerging research on how to solve various scheduling and logistics issues associated with airlines, including airport gate assignment, passenger boarding, air cargo scheduling, and fuel tankering.

Chun and Nordin [8] used a CPLEX algorithm to solve the problem of gate assignment to arriving aircraft in an airport. They sought to minimize the distance between arriving and departing gates in order to reduce customer walking time as well as luggage transfer distance. Another linear programming algorithm developed by Soolaki et al. [9] aims to solve the airline passenger boarding problem. The researchers strive to minimize overall boarding time while taking into account boarding constraints. Huang and Lu [10] develop a linear programming model with the goal of maximizing revenue for airlines managing air cargo requests. In their approach to solve the dynamic problem, they use two linear programming algorithms with a dynamic adjustment factor to simulate a dynamic algorithm solution. Fregnani and Correia [11] create a linear program for fuel tankering that minimizes total fuel costs for a domestic Brazilian airline by creating the optimal fueling schedule for an airplane in each airport that it visits. The model takes as constraints the total distance the airplane needs to fly for each leg and the fuel costs

and availability at both the departure and arrival airports. Algorithmic results demonstrate a 5% reduction in fuel costs for the airline.

## 3.3 The Use of Optimization and Linear Programming for Scheduling Problems

There are extensive past research studies and infinite future possibilities of applying optimization and linear programming to non-aerospace industries. A select few are described in this section.

Bulbul and Kaminsky [12] explore a general linear programming heuristic for solving various job shop problems. They strive to demonstrate a very general linear programming approach that can be applied to job scheduling problems in various industries.

Taking one industry as an example, the medical industry has many scheduling problems that can be addressed by Linear Programming. In the early 1980s, Hilal and Erikson [13] used a linear program to determine the most optimal combination of suppliers to meet the demand for heart valve production. The results of this study had a significant impact on reducing annual costs by $1.5M as well as improving life-saving product availability. More recently, Rieb [14] was able to develop an optimization algorithm to increase patient throughput in a cancer treatment unit at Massachusetts General Hospital in 2015. As a result of this algorithm, a 33% capacity increase potential was demonstrated during peak time at the hospital.

Shifting gears to the television industry, Garcia-Villoria and Salhi [15] developed a mixed integer linear programming algorithm to schedule commercial advertisements for television in 2015. This was another example of a complex scheduling problem with many advertising time slots and various advertiser requests involved. The constraints in this program deal with the advertiser requirement of spacing out repeat airings of the same commercial as well as with audience ratings.

Chapados et al [16] utilized mixed integer programming to maximize profits in retail stores by optimizing retail employee scheduling.

Due to these solutions being highly customized to their industries and some being proprietary, they cannot be applied directly to the EDC processes. However, the success stories and the general methodologies used prove the possibility of a successful application of optimization at the EDC.

## 3.4 Chapter Summary

Literature review of similar work showed that applying a mixed integer linear program will be a useful tool for the Everett Delivery Center paint and stall scheduling problems. Past work showed a few different ways to address the dynamic aspect of the problem. Martin, Jones, and Keskinocak's algorithm would re-run every time there was a schedule update, while Huang and Lu used two linear programming models with a dynamic adjustment factor to simulate the dynamic nature of the problem. For the purposes of this research study, there will be an assumption of static scheduling. Once the concept can be proved for a static problem, future iterations can address the dynamic aspect of EDC scheduling.

*This page has been intentionally left blank.*

# Chapter 4

# Methodology and Technology Selection

## 4.1 Methodology

To achieve the goal of assessing the potential impact of utilizing optimization technology for scheduling processes at the Everett Delivery Center, the task was split up into two separate problems. There were two existing manual scheduling processes identified in this study that could each benefit from optimization technology:

1. Paint Hangar Scheduling
2. Airplane Stall Scheduling

The paint hangar scheduling process occurs independently of the airplane stall scheduling process. The airplane stall scheduling process then takes the paint hangar schedule as one of its many inputs. The painting step is highly specialized in nature and is a shared resource between programs. As a result, it has the potential to be a bottleneck of the entire Everett Delivery Center ecosystem. The problem formulation for the paint hangar scheduling process is a lot more manageable in complexity than the airplane stall scheduling process. While both processes ultimately handle an equal amount of airplane throughput, paint hangar scheduling only has one task to schedule for each airplane and under 10 hangar locations to choose from. Comparatively, the airplane stall scheduling process has three or more tasks to schedule for each airplane and a choice of more than 30 stall locations. Additionally, there is a lot more complexity with the latter process in terms of operational rules and constraints to follow for

each of the three tasks. The paint process also has complexity associated with operational rules and constraints that have impact on scheduling, however as there is only one task involved, the problem formulation will be much less complex in comparison.

The methodology of this study was to first conduct an optimization pilot study with the paint hangar scheduling process and use its resulting optimization model as a baseline for the larger and more complex stall scheduling process problem.

## 4.2 Technology Selection

As the use of specialized commercial optimization technology was not feasible for the purpose of this study, the optimization modeling was conducted in collaboration with Boeing's internal Applied Math department. This group has developed various optimization algorithms for internal Boeing use. Two computing tools were determined to be the best fit for optimizing the two Everett Delivery Center scheduling processes:

1. Python tool
2. Excel VBA tool

The Python tool has the capability to handle larger problems and has more computing power, while the Excel VBA tool has a much higher potential of adoption and future maintenance by the EDC scheduling teams. Due to ease of future use and supportability by existing scheduling personnel, the Excel VBA tool was deemed appropriate. Furthermore, as most of the existing scheduling processes are handled through Microsoft Excel, the natural integration of this tool with existing processes made it the more desirable choice for both paint and stall scheduling.

## 4.3 Chapter Summary

This study selected paint hangar scheduling and airplane stall scheduling processes for evaluating the benefits of using optimization technology. The paint hangar scheduling process was evaluated first as a pilot due to its smaller scope. Two existing computing tools, which were developed by Boeing's Applied Math department were considered. Due to ease of future use and integration, the Excel VBA based tool was selected for the optimization of both processes.

*This page has been intentionally left blank.*

# Chapter 5

# Paint Hangar Scheduling Algorithm Development and Results

The paint hangar scheduling algorithm was developed with the goal of analyzing potential cost savings compared to a manual scheduling process. Since different paint hangars carry different costs with them based on complex contracts, it is difficult for a manual scheduler to see the most cost-effective solution, whereas an algorithm could do the task with ease. Each paint hangar may have different costs of painting due to factors such as available equipment, aircraft throughput, local labor and operating costs. Additionally, there are utilization ground rules in place to maintain a level load for labor.

The existing paint hangar scheduling process takes into account the costs and contractual obligations involved. The purpose of this paint scheduling algorithm is to minimize the overall painting costs by assigning airplanes to the most cost-efficient paint hangars. Boeing management will be able to see how much they could save on painting costs if the paint hangar location decisions were made based on cost only, and thus how much accommodating intangible factors is actually costing them.

## 5.1 Assumptions

Table 2: Paint Hangar Scheduling Algorithm Assumptions

| Assumption # | Assumption |
|---|---|
| **A1** | The paint start and end dates for each airplane are fixed and based on the original input schedule (delays and hangar variations are not taken into account for simplicity) |
| **A2** | The additional required travel time for off-site hangars is ignored |
| **A3** | Any airplane can be painted in any location and in any hangar |
| **A4** | One calendar year schedule was considered |
| **A5** | Each airplane must be painted in one and only one paint hangar |
| **A6** | Only one airplane can fit into each hangar at one time |
| **A7** | Each paint hangar location type will be assigned a normalized cost based on historical data. This normalized cost accounts for the difference in cost per airplane for painting at these different locations. |

## 5.2 Problem Formulation

This algorithm was set up as a Mixed Integer Linear Program.

### 5.2.1 Variables

$$X_{ahd} = \begin{cases} 1 & if\ airplane\ a\ gets\ assigned\ to\ hangar\ h\ on\ day\ d \\ 0 & otherwise \end{cases}$$

### 5.2.2 Objective

$$\min \sum_a \sum_h X_{ah} C_h$$

where

$$C_h = contractual\ cost\ of\ painting\ an\ airplane\ in\ hangar\ h\ (based\ on\ hangar\ site)$$

For the (contractual) types of costs considered, the formulation does not take into account variability of painting duration. Each aircraft a has a set of days d on which it must be painted. The contractual obligations are calculated with a developed macro after the algorithm runs the optimization.

### 5.2.3 Constraints

1) Each airplane must be assigned to a hangar

$$\sum_h X_{ah} = 1\ for\ all\ aircraft\ a$$

2) Each hangar can be assigned at most one aircraft each day

$$\sum_a \sum_d X_{ahd} \leq 1\ for\ all\ hangars\ h\ on\ each\ day\ d$$

3) Hangar cannot have any aircraft in it during a reserved window

$$\sum_a \sum_x X_{ahs} = 0\ for\ all\ hangars\ h\ on\ each\ day\ s\ of\ its\ reserved\ window$$

## 5.3 Algorithm Input

The input to the paint hangar algorithm was the EDC paint schedule that is manually produced as part of the existing paint planning process. This schedule is an excel file that shows all of the airplanes that are scheduled for each of the hangars on a daily basis for an entire year. Each airplane is labeled with a unique identifier, based on the name of the client that ordered that airplane as well as on the sequential number of the airplane based on its program (also known

as its line number). Furthermore, each airplane is color coded to represent which program it belongs to (747, 767, 777, or 787). A sample of this schedule can be seen in Figure 5.

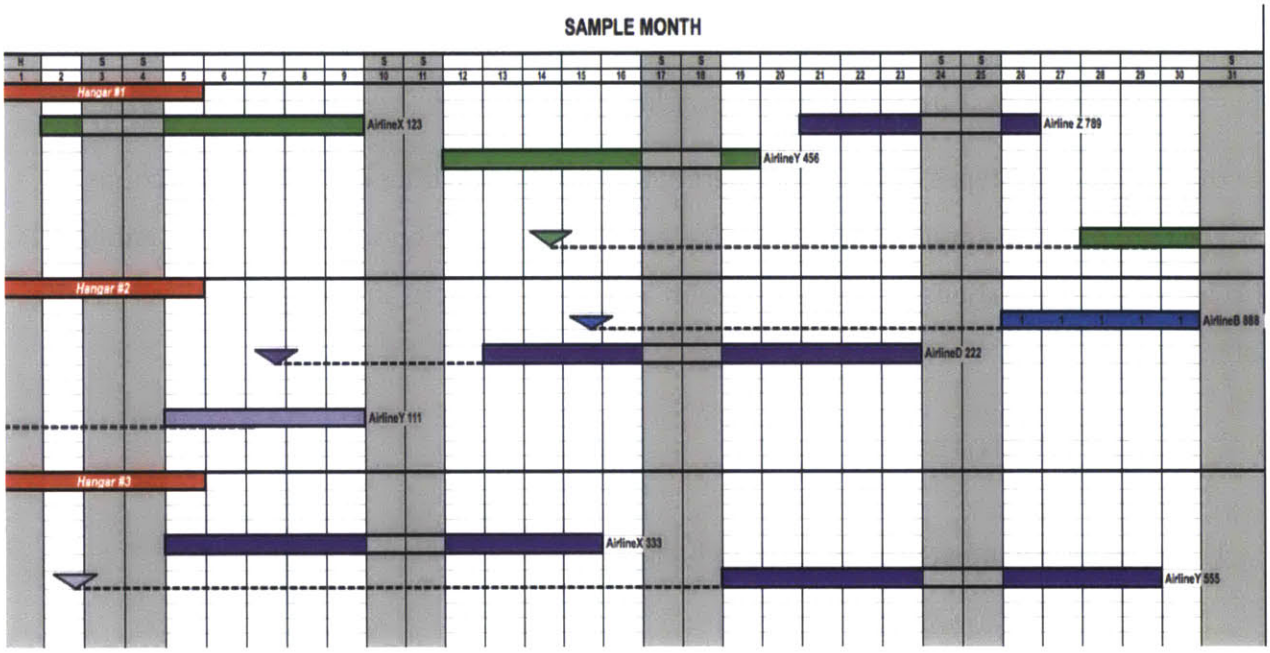


Figure 5: Sample Paint Hangar Schedule

The algorithm also allowed for the input of reserved hangar windows. Both Boeing-operated and Contractor-operated paint hangars require maintenance. The contractor-operated hangars may also be blocked off for other client reservation. The algorithm took the hangar name, start date of the block, and end date of the block as inputs to ensure no airplanes would be scheduled on those dates in those hangars.

## 5.4 Algorithm Steps

The Excel VBA algorithm executed the following steps:

1. Convert the visual paint schedule into tabular format

2. Calculate costs for the existing schedule, based on per-airplane costs obtained from historic data for each location
3. Run optimization logic to minimize contractual painting costs by assigning each airplane to the most cost-efficient location, with on-site hangars being the most cost efficient, and each of the off-site location carrying their corresponding costs
4. Output the optimized schedule in tabular format
5. Calculate costs for the optimized solution, based on per-airplane costs obtained from historic data for each location

The first step extracted the hangar identifier, program, start date, end date, paint duration, and airplane identifier for each of the airplanes from the visual paint schedule into a table. Next, a cost calculator was built based on hangar costs and operating rules. The costs can depend on any combination of program type, monthly minimum number of airplanes to be met, monthly minimum number of paint days to be met, and more. Different program types have different base costs. Additional utilization-based incentives and penalties can be incurred. The algorithm aggregated all of the paint hangar utilization data, organized by program and month, into a table for calculations based on all of the contractual obligation rules. A sample of this table can be seen in Figure 6. For confidentiality purposes, the data in this table is disguised through a random number generator. Once the costs of the existing manual solution were calculated, the algorithm ran the optimization logic, and then re-calculated the costs based on the optimized schedule created by the algorithm.

| Hangar | Program | January | February | March | April | May | June | July | August | September | October | November | December | Total Year | Program | Hangar |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 0 | 2 | 1 | 3 | 3 | 3 | 2 | 2 | 1 | 0 | 1 | 2 | 20 | A | 1 |
| | B | 3 | 2 | 1 | 1 | 2 | 0 | 2 | 1 | 3 | 3 | 3 | 3 | 24 | B | |
| | C | 3 | 0 | 2 | 2 | 1 | 3 | 1 | 0 | 0 | 2 | 1 | 0 | 15 | C | |
| | D | 0 | 3 | 3 | 0 | 2 | 3 | 1 | 1 | 1 | 2 | 0 | 2 | 18 | D | |
| 2 | A | 2 | 1 | 3 | 2 | 0 | 3 | 2 | 1 | 3 | 1 | 0 | 1 | 19 | A | 2 |
| | B | 2 | 1 | 1 | 0 | 3 | 3 | 0 | 0 | 3 | 3 | 1 | 2 | 19 | B | |
| | C | 3 | 0 | 0 | 1 | 2 | 0 | 2 | 2 | 3 | 1 | 3 | 3 | 20 | C | |
| | D | 3 | 3 | 3 | 3 | 0 | 1 | 3 | 2 | 2 | 1 | 2 | 0 | 23 | D | |
| 3 | A | 0 | 3 | 0 | 1 | 2 | 0 | 3 | 1 | 0 | 2 | 3 | 2 | 17 | A | 3 |
| | B | 3 | 0 | 2 | 1 | 0 | 3 | 0 | 1 | 3 | 2 | 3 | 1 | 19 | B | |
| | C | 1 | 3 | 2 | 3 | 3 | 0 | 2 | 2 | 3 | 3 | 1 | 3 | 26 | C | |
| | D | 0 | 1 | 1 | 0 | 2 | 1 | 2 | 3 | 3 | 3 | 3 | 1 | 20 | D | |
| 4 | A | 2 | 3 | 2 | 2 | 0 | 2 | 3 | 2 | 1 | 1 | 3 | 2 | 23 | A | 4 |
| | B | 1 | 3 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 20 | B | |
| | C | 0 | 1 | 1 | 1 | 3 | 2 | 2 | 2 | 0 | 0 | 3 | 3 | 18 | C | |
| | D | 1 | 2 | 0 | 1 | 1 | 0 | 1 | 3 | 2 | 1 | 2 | 0 | 14 | D | |
| 5 | A | 3 | 3 | 2 | 3 | 3 | 2 | 1 | 2 | 0 | 1 | 0 | 3 | 23 | A | 5 |
| | B | 0 | 0 | 0 | 3 | 3 | 0 | 2 | 2 | 1 | 1 | 1 | 0 | 13 | B | |
| | C | 1 | 3 | 0 | 0 | 2 | 1 | 1 | 2 | 0 | 0 | 1 | 3 | 14 | C | |
| | D | 0 | 1 | 3 | 2 | 3 | 2 | 0 | 2 | 1 | 1 | 3 | 0 | 18 | D | |

Figure 6: Sample Paint Hangar Cost Calculating Table

## 5.5 Algorithm Output

The algorithm output a new proposed optimized schedule and used all of the contractual cost rules to calculate the new overall cost for the hangar assignment schedule using the proposed optimized solution.

## 5.6 Results

Two years' worth of paint scheduling data was available for testing of this algorithm. Resulting potential savings vary from 13% to 35% based on variations of scheduled airline deliveries. Certain assumptions were made to simplify the problem formulation. A table with these assumptions can be seen in section 5.5.

Assumption 1 implies that all dates are set in stone, does not allow for any delays, and ignores the additional travel time required when an aircraft has to be flown off-site and back for its paint phase. In addition to the required flying time, different hangars have different equipment and as a result a paint job that would take five days to paint in one hangar could take several extra days to paint in another hangar. This additional time is also ignored in this problem formulation.

Assumption 3 implies that any airplane can get painted in any hangar. While theoretically that is true, in reality that does not always happen. Additionally, there could be variation in paint time between hangars.

The cost savings generated by the algorithm are a result of optimizing for minimizing penalty fees by ensuring that each airplane is always painted in the lower-cost hangar. There is a significant cost difference between hangar locations, so the algorithm always favors the cheaper location, if it is feasible. Existing manual schedules do not always do that due to decisions about other factors that are involved. The results of this study quantify the cost of these decisions to Boeing. Boeing will now have a tool that can quantify these decisions. For example, there is a frequent need for the EDC paint team to run different scenarios, or options, for where a set of airplanes can be painted in a given timeframe. Without the algorithm, the paint team member would need to submit a request to the finance team and wait for a response, which can take up to a few days depending on the availability of the finance team. It is thus currently difficult to estimate costs of each scenario as it occurs. With the development of this tool, the cost of the scenario can be calculated within a few seconds, without involvement of the finance team. This tool will thus allow management to have instantaneous insight into costs of each scenario.

## 5.7 Future Work

The algorithm developed in this thesis assumes that the dates involved are static. While this assumption was made in order to simplify the algorithm formulation, it does not reflect reality. Operationally, there could be delays in the process prior to paint, which would result in an alternative painting start date. These delays are out of control of the Everett Delivery Center, cannot be predicted by the Everett Delivery Center, and can create a domino effect of painting delays for multiple airplanes.

The livery painting job itself could also get delayed. This type of delay is within control of the Everett Delivery Center and could be predicted based on historical data about each customer's livery complexity and the number of times that livery has been executed before by each paint hangar. Boeing customers use paint liveries to distinguish their brand. Naturally there is an incentive there for the customers to design and request unique liveries. Some may include non-standard paint that has a shimmer to it. Others may involve images in addition to logos, which could be further complicated by complex shading and color blending. More complicated designs carry the potential to delay the required paint time to ensure the aircraft paint job is up to the customer's standards.

Any future iteration of the paint hangar scheduling algorithm should take into account the dynamic nature of both predictable and unpredictable painting date and duration changes.

## 5.8 Chapter Summary

A paint hangar scheduling algorithm was developed in order to gain visibility into potential cost savings by deciding on paint hangar location for each aircraft based on cost alone. This differs from the existing manual process, which deliberately favors locations based on customer preferences rather than cost. The algorithm showed a potential of cost savings in the range of 13-35% based on the year's delivery schedule. While leadership may choose to continue assigning paint hangar location for each airplane based on the customer's preference, it is necessary for them to have visibility into the financial impact of this decision, which is quantified by the developed algorithm. This algorithm made assumptions about painting dates being static. In reality, there are many causes of delays and date changes that are in play. Therefore, any future iteration of this algorithm should take into account the dynamic nature of these uncertainties.

# Chapter 6

# Stall Scheduling Algorithm Development and Results

The stall scheduling algorithm was developed after the successful pilot of the paint hangar scheduling algorithm with the goal of analyzing potential cost savings compared to a manual scheduling process. The goal of this algorithm is to minimize the total number of stall moves in the system. Each stall move entails a concrete cost that was calculated by Boeing but will be omitted in this publication for confidentiality reasons. Thus, by minimizing the total number of stall moves, the algorithm will also minimize costs. The resulting difference in stall moves will correspond to a concrete cost avoidance amount.

The stall scheduling problem is a lot more complex compared to the paint problem, which results in near impossibility for the manual scheduler to attain a cost optimal solution. While an algorithm theoretically should be able to find the most cost optimal solution, the algorithm developed in this research study ultimately was not able to accommodate the complexity of the problem.

## 6.1 Assumptions

Table 3: Stall Move Scheduling Algorithm Assumptions

| Assumption # | Assumption |
|---|---|

| | |
|---|---|
| **A1** | The steps involved in the process are paint, fuel, final inspection, and delivery |
| **A2** | Provided paint schedules and hangar assignments are set and cannot be changed |
| **A3** | An aircraft can only be assigned to one location (i) at a time (an aircraft cannot be in more than once place at the same time) |
| **A4** | Only one airplane can fit into each location (i) (each location can only accommodate one airplane at a time) |
| **A5** | An aircraft cannot go into a paint hangar with fuel in it, so Paint step should precede Fuel |
| **A6** | Location "i" is assigned as follows:<br>$1 \leq i \leq PH$: Paint hangars, where PH is the number of paint hangars<br>$PH+1 \leq i \leq PH+1+FS$: Fuel stalls, where FS is the number of fuell stalls<br>$PH+2+FS \leq i \leq PH+2+FS + PS$: Production stalls, where PS is the number of production stalls<br>$PH+3+FS + PS \leq i \leq PH+3+FS + PS + DS$: Delivery stalls, where DS is the number of delivery stalls<br>$PH+4+FS + PS + DS \leq i \leq PH+4+FS + PS + DS + SS$: Storage stalls, where SS is the number of storage stalls |
| **A7** | All paint hangars will be treated as on-site for simplicity |
| **A8** | All fuel dock stalls are interchangeable |
| **A9** | All airplanes deliver out of a delivery stall for simplicity |
| **A10** | Storage stalls are available for overflow capacity |
| **A11** | A time period of 1 year will be considered |

## 6.2 Problem Formulation

The stall scheduling problem is formulated as a network Mixed Integer Linear Program.

### 6.2.1 Variables

$$x_{aijt} = \begin{cases} 1 & if\ aircraft\ a\ starts\ in\ stall\ i\ and\ moves\ to\ stall\ j\ in\ time\ period\ t \\ 0 & otherwise \end{cases}$$

### 6.2.2 Objective

$$\min \sum_{(a,i,j,t)\in I1} p(a,i,j)x_{aijt}$$

Here,

- I1 = set of all possible aircraft a, location i, location j, time period t combinations
- p(a,i,j) = penalty for aircraft a moving from location i to location j. This penalty is calibrated to the actual cost incurred from each stall move.

### 6.2.3 Constraints

1) Network flow balance (the number of aircraft going into nodes must equal the number of aircraft coming out)

$$\sum_{(j)\in I2(a,i,t)} X_{aijt} - \sum_{(k)\in I3(a,j,t+1)} x_{ajk,t+1} = s(a,j,t)$$

$for\ all\ possible\ aircraft\ a, node\ j, time\ period\ t\ combinations$

2) Number of days each aircraft must spend in a stall type

$$\sum_{(i,j,t)\in I4(a,st)} x_{aijt} = NS(a,st)$$

$for\ all\ possible\ aircraft\ a\ and\ stall\ type\ requirements\ st$

3) Only one aircraft can be in a stall at one time

$$\sum_{(a,j)\in I5(i,t)} x_{aijt} \leq 1$$

$for\ all\ possible\ stations\ i\ and\ time\ periods\ t$

4) Integer variable constraints

$x_{aijt} \in \{0,1\}$

$for\ all\ possible\ (a,i,j,t) \in I1$

Here,

- I2(a,i,t) = set of possible stations j such that aircraft a can transition from station i at time period t to station j in time period t + 1
- I3(a,j,t+1) = set of possible stations i such that aircraft a can transition from station j at time period t +1 to station k
- s(a,j,t) = 1 if aircraft a goes to final delivery at stations j at time t + 1; = -1 if aircraft a starts path in network at station j at time period t + 1
- I4(a,st) = set of (i,j,t) such that aircraft a can transition from station i to station j starting in time period t for station type st
- NS(a,st) = number of time periods that aircraft a must be at a station for station type st
- I5(i,t) = set of possible (a, j) such that aircraft a can transition from station i to station j starting in time period t

# 6.3 Algorithm Input

The input to the stall scheduling algorithm was the EDC stall allocation schedule that is manually produced as part of the existing stall planning process. Similar to the paint input file, this schedule is also an excel file that has unique formatting to show all of the airplanes that are scheduled for each stall on a daily basis. Each stall has its own column and stall columns are sorted by type. Airplanes are identified by their line numbers and color-coded based on the crew that is assigned to work on them. Each crew has its own home stall, and whenever possible, an airplane should be serviced by one crew in its home stall. When that cannot be achieved, an assigned crew can travel to a different stall to service their assigned airplane. At other times, a crew may have to hand off the airplane to a different crew. A sample schedule with a small subset of stalls can be seen in Figure 7.

| YEAR | Fuel Dock | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Program A | Program B | Program C | Program D | Program D | Production Stall 1 | Production Stall 2 | Production Stall 3 | Production Stall 4 | Production Stall 5 | Production Stall 6 | Production Stall 7 | Delivery Stall | Delivery Stall |
| DATE | F1 | F2 | F3 | F4 | F5 | 109 | 201 | 202 | 110 | 111 | 204 | 205 | 207 | 208 |
| 1-Dec | 1 | | | 1122 | | 345 | 700 | 333 | | 1111 | 5550 | 7777 | 8787 | 6666 |
| 2-Dec | | | | 1122 | 9999 | 345 | 700 | 333 | | 1111 | 5550 | 7777 | 8787 | 6666 |
| 3-Dec | | | | 1122 | 9999 | 345 | 700 | 333 | 1234 | 1111 | 5550 | 7777 | 8787 | 6666 |
| 4-Dec | | | | 1122 | 9999 | 345 | 700 | 333 | 1234 | 1111 | 5550 | 7777 | 8787 | 666 |
| 5-Dec | | | | | 9999 | 345 | 700 | 333 | 1234 | | 5550 | 7777 | 8787 | 6666 |
| 6-Dec | 222 | 211 | | | 9999 | 345 | 700 | 333 | 1234 | | 5550 | 7777 | 8787 | 6666 |
| 7-Dec | 222 | 211 | | | 9999 | 345 | 700 | 333 | 1234 | | 5550 | 7777 | 8787 | 6666 |
| 8-Dec | 222 | 211 | 444 | 1266 | 9999 | 345 | 700 | 333 | 1234 | | 5550 | 7777 | 8787 | 6666 |
| 9-Dec | 222 | 211 | | 1266 | 9999 | 345 | 700 | 333 | 1234 | | 5550 | 7777 | | 6666 |
| 10-Dec | 222 | 211 | 444 | | 7878 | 345 | 700 | | 1234 | | 5550 | 7777 | | 6666 |
| 11-Dec | 222 | 211 | 444 | | 7878 | 345 | 700 | | 1234 | | 5550 | 7777 | | 6666 |
| 12-Dec | 222 | 211 | 444 | | 9999 | 345 | 700 | 11 | 1234 | | 5550 | 7777 | 7878 | 6666 |
| 13-Dec | | 211 | | | 9999 | 345 | 700 | 11 | 1234 | | | 7777 | 7878 | 6666 |
| 14-Dec | 1111 | 211 | | | 9999 | 345 | 700 | 11 | 1234 | | | 7777 | 7878 | 6666 |
| 15-Dec | 1111 | 211 | | | | 345 | | 555 | 1234 | | | 7777 | 7878 | 6666 |
| 16-Dec | | 211 | | | | 345 | | 555 | 1234 | 1111 | | 7777 | 7878 | 6666 |
| 17-Dec | | 211 | | | | 345 | 700 | 555 | 1234 | 1111 | | 7777 | 7878 | 6666 |
| 18-Dec | | 211 | | | | 345 | 700 | 555 | 1234 | 1111 | | 7777 | 7878 | 4444 |
| 19-Dec | | 211 | | | | 345 | 700 | | 1234 | 1111 | | 7777 | | 4444 |
| 20-Dec | | 211 | | | | | 700 | 555 | 1122 | 1111 | | 7777 | | 4444 |
| 21-Dec | | 211 | | | | | 700 | 555 | 1122 | 1111 | | 7777 | | 4444 |
| 22-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | | 7777 | 12 | 4444 |
| 23-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | 12 | 4444 |
| 24-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| 25-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| 26-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| 27-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| 28-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| 29-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| 30-Dec | 7777 | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| 31-Dec | | | | | | | 700 | 555 | 1122 | 1111 | 7777 | | | 4444 |
| | | | | | | | | | | | 7777 | | | |

Figure 7: Sample Stall Move Schedule

## 6.4 Algorithm Steps

Similar to the paint algorithm, the stall optimization Excel VBA algorithm was designed to execute the following steps:

1. Convert the visual stall schedule into a tabular format
2. Calculate the number of moves and their corresponding costs for the existing schedule
3. Run optimization logic by analyzing all possible paths for each airplane and choosing the paths that result in the least amount of total moves (and thus costs) for the whole system
4. Output the optimized schedule in a tabular format
5. Calculate the number of moves and their corresponding costs for the optimized solution

As the first step, the algorithm converted the visual input schedule into a table that shows the program, line number, activity, start date, end date, activity duration, and assigned location for each aircraft. The total number of moves associated with the existing schedule is then calculated and the optimization algorithm is run.

## 6.5 Algorithm Output

Once the algorithm concludes its computations, the resulting new schedule would be displayed, and the number of moves resulting from the optimized solution would be shown.

## 6.6 Results

The Excel VBA tool proved to be not robust enough to handle the size of the problem at hand. Further tests were conducted to decrease the number of variables involved by reducing the

time outlook from one year to one month, and even then the optimization technology was not performing.

An alternative analysis was performed on the stall move scheduling process to determine ways to reduce the yearly amount of stall moves. Three scenarios were considered:

1. Local paint capacity increase
2. Fueling prior to PF&D
3. Interchangeable Stalls

This analysis was conducted by examining past stall schedules and manually re-arranging the airplanes into different stalls according to each scenario, with the goal of minimizing overall stall moves. All of the existing dates and stall scheduling requirements were honored. The total number of moves after the retroactive changes was calculated and compared with the actual number of stall moves that occurred.

The first scenario analyzed the effect on total yearly stall moves if the five off-site paint hangars were made to be local. The second scenario focused the effect on total stall moves if the fuel step always preceded PF&D. The third and last scenario examined the scenario where PF&D stalls were all made to be interchangeable between programs. Table 5 outlines the results of these scenarios. Since the analysis was done manually, the reported numbers are likely lower bounds since an automated optimization is known to catch reduction opportunities manual analysis tends to miss.

Table 4: Stall Move Reduction Potential by Scenario

| Scenario | % Yearly Stall Move Reduction |
|---|---|
| **Local Paint** | 14% |
| **Fuel before Final Tests** | 12% |
| **Interchangeable Stalls** | 3% |

The local paint scenario was the most impactful to the reduction of yearly moves. However, it includes high capital costs and a long lead time since paint hangars require a large physical area of land.

Fueling before PF&D when possible will reduce stall moves without any required change to existing infrastructure, and therefore will be much easier to implement. Since some PF&D process steps, such as test flights, require the aircraft to be fueled, making sure fueling precedes PF&D will result in reduced number of moves. If fueling does not occur prior to PF&D, then an extra move will be introduced during PF&D to get the aircraft fueled before the test flights can be carried out.

Making PF&D stalls interchangeable does not yield a reduction as sizeable as the other two scenarios. This scenario would also require changes to existing stall infrastructure, such as expanding the size of some existing stalls to be able to accommodate the largest aircraft program, which may not be worth the small stall move reduction.

## 6.7 Future Work

The selected optimization technology was deemed unsatisfactory for the size of the stall scheduling problem. The Boeing Applied Math department has several other technologies that can be used in future studies to handle the complexity of the stall problem.

Additionally, the attempted algorithm made assumptions that the dates involved are static. While this assumption was made in order to simplify the algorithm formulation, it does not reflect reality. Operationally, there could be delays in any of the process steps, or even the delivery itself.

Some delays are out of control of the Everett Delivery Center, such as a factory rollout date change. A delay of one plane can create a domino effect of changes for other airplanes in the EDC workflow.

The EDC handles many complex processes and its operations are dynamic in nature. Therefore, in addition to using a more robust optimization technology, future work should be able to account for changes to the system on a frequent basis.

## 6.8 Chapter Summary

The stall scheduling algorithm was developed after the successful pilot of the paint hangar scheduling algorithm with the goal of analyzing potential cost savings compared to a manual scheduling process. Due to the much more complex nature of this problem compared to the paint problem, the selected technology was deemed not robust enough to provide a useful solution. A manual analysis was then performed to evaluate potential scenarios to further reduce stall moves by retroactively analyzing past data. There is evidence for potential to reduce stall moves with the use of optimization technology. Future work should select a more robust optimization technology as well as account for uncertainty in the schedule.

*This page has been intentionally left blank.*

# Chapter 7

# Conclusion and Recommendations

Introducing cost minimizing paint optimization showed a significant potential impact for Boeing's painting costs. While Boeing may decide other operational business factors have more significance than cost of the painting locations, it is nonetheless important for leadership to have visibility into cost implications of such decisions.

In the case of stall move optimization, despite the selected algorithm not being able to handle the problem complexity, further analysis demonstrated that there is room for improvement in number of stall moves. Past success stories with similar problems, such as FAO companies [6], showed a significant cost reduction when optimization software was introduced to a complex scheduling process. It is therefore a recommendation of this study that Everett Delivery Center leadership considers implementing scheduling software that will be able to optimize the EDC processes end to end, from paint to delivery. Similar to the FAO software, it will be crucial for this software to handle the dynamic nature of operations, as well as to give scheduling personnel the flexibility to make operational decisions and override the optimal schedule if necessary.

*This page has been intentionally left blank.*

# Bibliography


[1] I. Lustig, "Optimization-Based Solutions: Smarter Decisions for a Smarter Planet." 28-Apr-2011.

[2] "Boeing: Boeing in Everett, Wash." [Online]. Available: http://www.boeing.com/company/about-bca/everett-production-facility.page. [Accessed: 22-Feb-2016].

[3] "Boeing: Commercial." [Online]. Available: http://www.boeing.com/commercial/#/orders-deliveries. [Accessed: 05-Feb-2016].

[4] M. L. Pinedo, *Scheduling*, 4th ed. 2012 edition. Springer, 2013.

[5] *Production and Operations Analysis*, 6 edition. New York, NY: McGraw-Hill/Irwin, 2008.

[6] C. Martin, D. Jones, and P. Keskinocak, "Optimizing On-Demand Aircraft Schedules for Fractional Aircraft Operators," *Interfaces*, vol. 33, no. 5, pp. 22–35, Oct. 2003.

[7] S. Douglas Indika, Shier, "Optimization Models for Scheduling of Jobs," *J. Res. NIST*, vol. 111, no. 2, pp. 103–111, Apr. 2006.

[8] C. K. Chun and S. Z. Nordin, "An integer programming model for gate assignment problem at airline terminals," in *AIP Conference Proceedings*, 2015, vol. 1660, p. 090031.

[9] M. Soolaki, I. Mahdavi, N. Mahdavi-Amiri, R. Hassanzadeh, and A. Aghajani, "A new linear programming approach and genetic algorithm for solving airline boarding problem," *Appl. Math. Model.*, vol. 36, no. 9, pp. 4060–4072, Sep. 2012.

[10] K. Huang and H. Lu, "A linear programming-based method for the network revenue management problem of air cargo," *Transp. Res. Part C Emerg. Technol.*, vol. 59, pp. 248–259, Oct. 2015.

[11] J. A. T. Guerreiro Fregnani, C. Müller, and A. R. Correia, "A fuel tankering model applied to a domestic airline network," *J. Adv. Transp.*, vol. 47, no. 4, pp. 386–398, Jun. 2013.

[12] K. Bu¨lbu¨l and P. Kaminsky, "A linear programming-based method for job shop scheduling," *J. Sched.*, vol. 16, no. 2, pp. 161–183, Apr. 2013.

[13] S. S. Hilal and W. Erikson, "Matching supplies to save lives: linear programming the production of heart valves," *Interfaces*, vol. 11, pp. 48–56, Dec. 1981.

[14] W. Rieb, *Increasing patient throughput in the MGH Cancer Center Infusion Unit*. 2015.

[15] A. Garci´a-Villoria and S. Salhi, "Scheduling commercial advertisements for television," *Int. J. Prod. Res.*, vol. 53, no. 4, pp. 1198–1215, Jan. 2015.

[16] N. chapados@iro.umontreal.ca Chapados, M. marc.joliveau@gmail.com Joliveau, P. lecuyer@iro.umontreal.ca L'Ecuyer 3, and L.-M. louis-martin.rousseau@polymtl.ca Rousseau, "Retail store scheduling for profit," *Eur. J. Oper. Res.*, vol. 239, no. 3, pp. 609–624, Dec. 2014.