Implementation of Assembly Automation in Aircraft Structures

by

Zackary R. Eubanks

B.S.M.E., University of Arkansas, 2010
B.A., University of Arkansas, 2013

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Signature of Author _____ Signature redacted ___

MIT Sloan School of Management
Department of Mechanical Engineering

Certified by _____ Signature redacted May 12, 2017 ___

Dr. Roy Welsch, Thesis Supervisor
Professor of Management Science
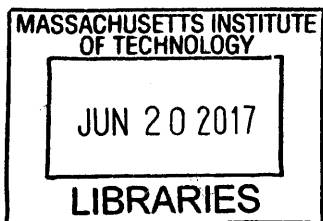MIT Sloan School of Management

Certified by _____ Signature redacted ___

Dr. Daniel E. Whitney, Thesis Supervisor
Senior Research Scientist, Emeritus
MIT Leaders for Global Operations

Accepted by _____ Signature redacted ___

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

Accepted by _____ Signature redacted ___

Rohan Abeyaratne, Chair of the Committee on Graduate Students
Department of Mechanical Engineering

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Abstract

Flexible automation for drilling and countersinking has been successfully implemented in the assembly of a small number of aircraft structures. These systems have demonstrated the capability to reduce the risk of repetitive use injuries, improve quality, and reduce labor costs. Despite these successes, disruptive delays to production resulted when similar technology was initially implemented in the assembly of 777 wing structures.

Baseline data was collected to analyze the performance of the system, and it was found that the delays were largely a result of machine breakdowns or error conditions during production. Three changes to the equipment and processes were prioritized because they could be quickly implemented and were expected to address some of the most-common causes of the in-process machine errors. Average drilling times were reduced by 5.9%, and maximum drilling times were reduced by 10% as a result of these changes. Process simulations based on the data demonstrated that the expected frequency of production delays was reduced from 37.4% to 17.6% of all wings produced.

Thesis Supervisor: Dr. Roy Welsch
Title: Professor of Management Science

Thesis Supervisor: Dr. Daniel E. Whitney
Title: Senior Research Scientist, Emeritus

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1 Introduction

In response to an increasingly-competitive market for commercial aircraft and factors inherent in the production process for these products, automation has been implemented in a wide range of applications by aerospace companies. While some processes easily lend themselves to automation using existing technologies, the assembly of aircraft structures presents a number of unique challenges that have left much of such work in the hands of skilled mechanics who continue to use proven manual processes. Despite the challenges of implementing automation in assembly applications, the potential benefits lead manufacturers to devote significant resources to the development of the technologies and organizational competencies needed to expand the reach of automation in their assembly lines.

One method that has proven effective in expanding the reach of automation in aircraft assembly is to develop flexible automated platforms that are dedicated to a specific type of process such as drilling or fastener insertion. Such systems can be implemented and incrementally improved in one application before adapting similar equipment to another type of structure or to another airplane model. The similarity in platforms allows expertise to be built within the organization and reduces the risk associated with the introduction of a new technology. However, each application is accompanied by a unique set of circumstances and requirements that can drastically impact the difficulty of incorporating the automated system.

This thesis is centered around the application of Flex Track, a proven class of automated drilling equipment, as a replacement for a long-established manual drilling process. Such an application provides an interesting case study because it allows for a direct comparison between the legacy manual process and the new automated process in an active production system. The challenges associated with implementing assembly automation here are likely to find parallels in future efforts to automate existing assembly processes, and the analytical methods used to generate

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recommendations for improving this system are extensible to other situations where assembly automation has been implemented or is under consideration.

2 <u>Background</u>

This chapter provides contextual and technical background that serves as a foundation for the chapters that follow. The company and industry context help to explain the motivation behind this research, while subsequent sections introduce relevant prior academic work.

2.1 Company and industry

The market for commercial wide-bodied jet aircraft is effectively split by Boeing and Airbus. Traditionally, Boeing has targeted the premium end of the market with high quality and leading fuel performance, while Airbus has competed on the basis of lower cost. In the current market, with low fuel costs, airlines are less sensitive to the fuel performance of the aircraft that they purchase. As a result, Boeing has seen an erosion of its market share in recent years.

Historically, the wide-bodied jet market is strongly cyclical. Demand for new aircraft is increased when airlines plan to open new long-distance routes or replace the older aircraft in their fleets. An excess supply of used aircraft that can fulfill the needs of airline customers can temper demand, especially when low fuel prices diminish the incremental operating cost savings associated with a newer, more efficient airplane.

As a result of these market conditions, there is significant pressure on Boeing to reduce the cost of its products. While costs reductions can be achieved in a variety of ways, manufacturing costs represent one of the company's primary targets for improvement. In its 2015 annual report, Boeing remarks that "major productivity gains are essential to ensure a favorable market position at acceptable profit margins [1]." Unlike cost savings generated from improvements in future designs, reductions in manufacturing costs have an immediate impact on profitability and the prices that can be offered to customers. As a result, increases in productivity can immediately be used in efforts to reclaim market share, leading to additional reductions in cost as economies of scale are leveraged.

Considering the immense labor costs involved in aircraft production and the prevalence of manual production methods, particularly in assembly processes, the increased use of assembly automation represents a potentially-valuable means of increasing productivity and improving cost competitiveness.

2.2 Automation in aerospace

Automated production methods have taken hold in the aerospace industry at a much slower pace than in other industries, such as automotive and pharmaceuticals. This can be attributed to the fact that many of the conditions inherent in aircraft production are also in conflict with the traditional enablers of automation. Low production volumes in aerospace and a wide range of complex assembly tasks leads to a high fixed cost per unit of production. Further, the precision required in aerospace assemblies with respect to the total part size can push the limits of typical robotic control systems.

Aerospace manufacturers face further challenges when developing and implementing automated systems for their factories. The design and development of a new commercial airplane requires on the order of ten years to complete, and the pressure to complete the development process on time leads designers to reuse legacy designs that are not optimized for automation [2]. As the systems are developed to assemble aircraft to the new design, both internal and external suppliers are developing their processes to produce the components. The time required to ramp up the fabrication of each new component combined with the high unit costs of such components leads to a situation where assembly automation has very few if any real parts available for development and testing. Unlike in the automotive industry where hundreds of development and validation parts can be run at relatively low cost, automated systems for aerospace assembly must be highly capable before touching the first part and often still require significant refinement to reach full rate production.

Despite the challenges presented above, aerospace manufacturers have a number of compelling reasons to face these challenges and embrace automation. While aerospace assemblies do not often achieve scale in the number of units sold, each unit contains a massive amount of work. Drilling, countersinking, deburring, and fastener insertion typically occur in great volumes on a large aerospace assembly. The repetitive loads that these tasks put on a worker's joints can often lead to injuries that diminish quality of life and are costly to the company. Repeated tasks also lend themselves to automated systems that are not susceptible to injury and can often outpace human workers in the tasks for which they are designed while maintaining a higher level of precision. Further, the long product lifecycle of a commercial airplane provides a long horizon to realize the benefits of large automation investments.

As the case for automating production has strengthened in the past decade and some of the industry-specific challenges have been mitigated through advancements in the capabilities of automated equipment, a body of research has also emerged that addresses some of systematic challenges that have historically inhibited the effectiveness of automation in aerospace manufacturing. Ezolino addresses the potential of Design for Assembly (DfA) to unlock new opportunities for the successful use of automation in manufacturing complex products [2]. McAfee investigates the appropriate amount of automation to be included in the fabrication of composite aircraft components [3], while Durham explores the appropriate automation levels for aerospace assemblies [4]. Frackleton proposes an improved method for assessing the risk of automation proposals from suppliers based on the Technical Readiness Level (TRL) framework [5]. Hume investigates the management of automation supplier relationships through the acquisition and acceptance phases of a project [6], and Ebner focuses on the buyoff process itself as a potential means to improving outcomes in automation projects [7].

Figure 1 provides a simplistic flow of an automation project from product design through system implementation. While previous academic work has focused on the steps preceding implementation, this thesis addresses the system implementation stage of an automation project.
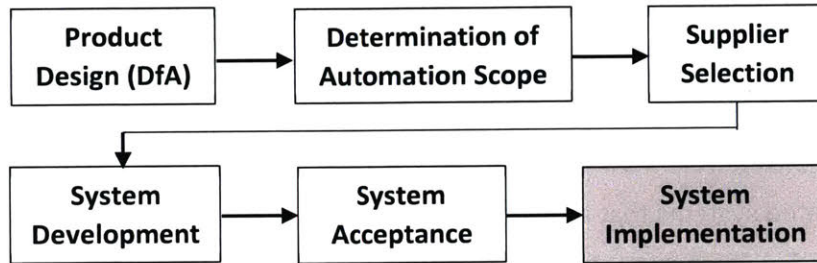
Figure 1: Simplistic flow of an automation project

2.3 Flex Track System

Flex Track refers to a class of automated equipment that was first developed by Boeing's Advanced Manufacturing Research and Technology (AMR&T) group to automate the drilling and fastening of large aircraft components. The system consists of a small CNC-controlled carriage mounted to a pair of rails that can be attached to the work piece using vacuum cups [8]. The carriage contains a drill spindle and a servo drive system that moves the carriage in three translational axes (along the rails and in two orthogonal axes) and in a rotational axis that is parallel to the track rails. This configuration allows the Flex Track to drill two-dimensional hole patterns on the surface where it is mounted, while simultaneously sensing and adjusting the rotational orientation of the drill spindle to ensure that each hole is drilled perpendicular to the work surface. Depending on the application, the Flex Track system can be designed for operating between the two tracks or in an configuration where the working envelope is offset from one side of the tracks [9].

The Flex Track carriage is connected to the CNC controller and to electrical power using a large cable, known as the "umbilical," with a high-voltage power plug and a multi-pin connector for

controls on both ends. An external vacuum is integrated with the system to remove chips and excess coolant as the machine drills. Each of the tracks' vacuum cups has its own vacuum generator that is supplied with compressed dry air from air lines at the ends of the tracks.

In circumferential applications, the tracks completely encircle the structure being drilled in such a way that the tracks and carriage cannot fall while in use. In other applications, tethers and fall-restraint carts are used in various configurations to prevent the carriage and tracks from falling in the event of an air supply loss to the vacuum cups. Complete uniformity of fall-restraint practices is not feasible because each application has different constraints related to the type of structure being drilled and the surroundings. While some applications require a dedicated structure to connect fall-restraint devices, other applications may have surrounding structures such as fixed assembly jigs (FAJs). The presence of such structures can often provide simple solutions for fall restraint that keep workers and equipment safe; however, the busy and tightly-packed environment of an FAJ can just as often make these tasks more difficult.

Flex Track has been successfully implemented in several assembly applications over the last decade. As a result of the maturity of the technology, the risk of implementing new systems in additional applications is diminished. Scaling such proven technologies across the company is a promising avenue for harnessing the benefits of automation with lower risk and lower development costs than could be achieved through the design of highly-customized automated systems that are tailored to each application.

3   Wing Structure Assembly

This chapter describes the methods used to assemble the primary structure of an aluminum airplane wing. Emphasis is placed on those aspects relevant to later discussions of the application of Flex Track automation.

3.1 Production in Fixed Assembly Jig

The assembly of each wing begins in a set of fixed assembly jigs (FAJs) that serve to locate components and provide the necessary access for mechanics to perform assembly work. Within the FAJ, a wing is constructed with the trailing edge nearest the ground and the leading edge on top. In addition to structures that facilitate work on the wing assembly, the FAJ must also contain or provide access to everything that is needed to produce a wing. This includes connections for electrical power and compressed air, a wide array of tools and production equipment, as well as all of the components that are to be installed.

As a result of the wide range of parts and processes used, the FAJ is a highly complex manufacturing environment. All tasks related to the wing assembly process are built in to a highly-detailed schedule that ensures that processes are carried out in the correct order and are completed in time to move the wing to its next position in the factory for further assembly. For each scheduled task, a mechanic with the correct skillset must have all of the parts and tools needed. To fulfill this requirement and to make sure that no task is inhibited by a clutter of parts and tools, space in and around the FAJ must be managed carefully.

Typically, one team of mechanics will specialize in a specific portion of the assembly process that corresponds with their skills and training. That team can only begin their work on a wing when certain critical steps are completed by the preceding teams. Likewise, subsequent teams depend on that team to complete certain steps before proceeding. Even minor delays in the installation of one

part can put the whole assembly process behind schedule, and overtime is frequently used as a means to recover from such delays.

3.2 Summary of Wing Build

The build process for a wing is extremely complicated and involves the precise assembly of thousands of parts. As such, this section only provides a high-level overview of the build process and introduces the key components that are involved.

The internal structure of the wing is composed of two spars and numerous ribs, which are assembled into the wing box. This structure that resembles a tapered ladder as shown in Figure 2.
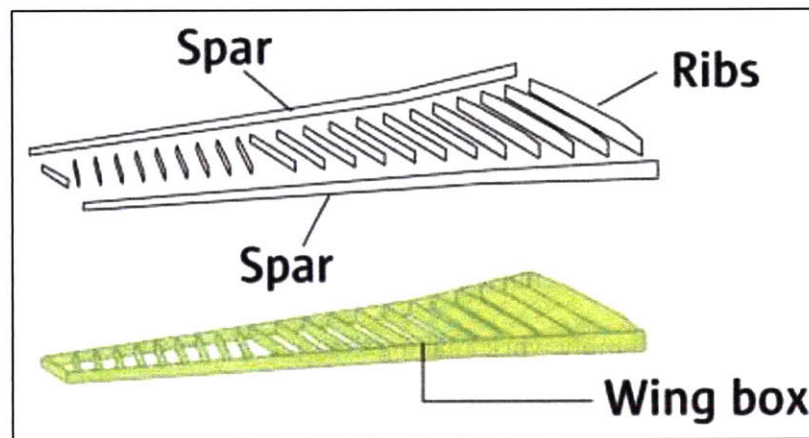
Figure 2: Illustration of wing box assembly [10]

The rear spar is the bottom-most component when the wing box is assembled in the FAJ. As such, it is the first of the wing box components to be installed. It is lowered by crane into a precise position and orientation in the FAJ before the ribs are located and attached. Finally, the front spar is lowered in on top of the ribs before the entire wing box structure is fastened together by a team of mechanics.

With the wing box completed, the upper skin panel assembly can be guided into place using overhead cranes. The upper panel is precisely located relative to the wing box assembly as shown

in Figure 3 and is clamped into place against the spars. Hundreds of fasteners are used to attach the wing panel to the spars and ribs, and the entire assembly must be carefully sealed to prevent fuel from leaking while in flight. The following section provides a more-detailed explanation of the process used to attach skin panels to spars.
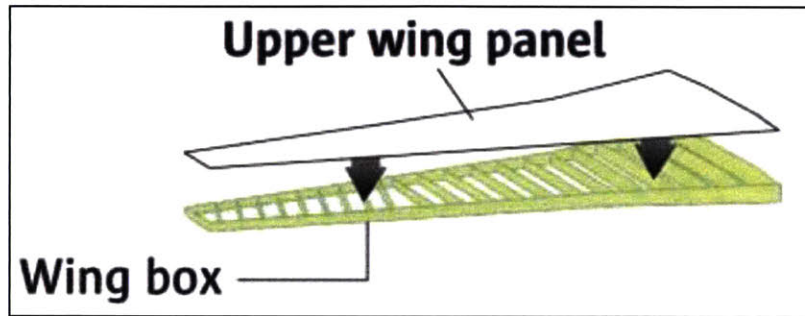
Figure 3: Illustration of wing panel installation [10]

With the upper skin panel securely fastened in place, a similar process is repeated for the lower skin panel. In this case, however, the presence of the upper panel blocks access to the inside of the wing. This means that mechanics must crawl through holes in the lower skin to get inside the wing to perform much of the assembly work, making their jobs more strenuous and time-consuming.

Once the lower panel is securely fastened in place, many of the fixed leading and trailing edge components of the wing are installed before the entire assembly is lifted from the FAJ by crane and taken to its next position in the factory.

3.3 Panel-to-Spar Join

As mentioned in the previous section, the installation of the wing skin panels is a critical step in the assembly of an airplane wing. This section introduces the key steps involved in joining the upper wing skin panel to the rear spar in order to provide context for later discussion of the scope of automation in the wing assembly process. Although only the upper panel and rear spar are

discussed here, the fundamental elements of the process remain the same for the remaining three panel-to-spar joints.

Once the upper skin panel is clamped into place against the wing box, the work of permanently attaching the two assemblies begins. The location, size, and type of each hole that must be drilled is precisely defined by design engineers, and great care must be taken to meet these specifications. In order to find the appropriate locations for the first holes in the skin panel, mechanics find reference holes that were previously drilled in the rear spar assembly. Larger holes are drilled through the skin panel and the spar assembly at these locations. Whether drilling manually or using automation, the locations of two such reference holes are used to define the two-dimensional grid that defines the center points of the remaining holes. Details of drilling and countersinking holes using both manual and automated methods are provided in later sections.

When all of the holes common to the upper skin panel and rear spar have been drilled and countersunk to their final dimensions and inspectors have verified that this work was done correctly, sealant must be applied between the two adjoining surfaces. Mechanics wedge one end of the skin panel away from the spar and clean any off any debris or oil that remains on the parts from drilling. A layer of sealant is applied before removing the wedge so that the process can be repeated on the adjacent section along the length of the wing.

With all of the holes drilled and the sealant applied, mechanics can then insert the fasteners that hold the two assemblies together. The type, material, and dimensions of each fastener are precisely defined for the location where it installed. The dimensions of the fastener correspond with the dimensions of the hole and the thickness of the material stack in which it is inserted. Most of the fasteners used in this application are Hi-Loks, which are aerospace-grade bolts with a tapered head and a threaded end that is secured by an internally-threaded collar. As the collar is installed, the wrenching element of the collar breaks off from the threaded portion when the targeted torque is

applied. These fasteners are driven into place from the skin panel side, then collars are installed from the spar side to complete the attachment of the skin panel to the spar.
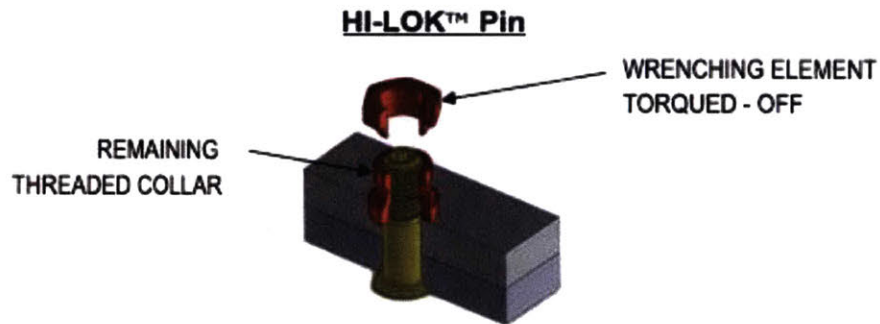
Figure 4: HI-LOK illustration from supplier website [11]

3.4 Manual Drilling and Countersinking

The drilling and countersinking holes in the wing structure has historically been very labor intensive. Hundreds of holes of various sizes must be precisely located and oriented relative to the components that are being joined. Once reference holes are drilled, they are used as attachment points for long, metallic jigs that guide the drill bits to the correct center point on the surface of the skin panel. Depending on a hole's size, it may require several drill bits of increasing size to reach its final diameter. The bottom surface where the drill bits broke through must then be deburred, removing any irregularity from the edge of the hole, in order to make sure that fasteners fit perfectly against the part.

With a set of cylindrical holes drilled to the appropriate specifications, the mechanic returns with a countersink tool to create a conically-tapered opening to the hole. This allows the hole to accept a fastener with tapered head that sits flush with the surface of the skin panel. Flushness is critical for fasteners on the exterior of the wing because even a small protrusion can cause drag by interrupting the laminar flow of air.

Achieving the appropriate fit between the fastener and the countersunk hole depends on the angle of the countersink's taper, the diameter of the taper at the surface of the hole, and the angular relationship between the axis of the countersink and the axis of the cylindrical hole. The angle of the countersink's taper is determined by the geometry of the tool used, while the diameter at the surface depends on the depth to which the tool is inserted. A smooth mandrel is often attached to the front of the countersink tool to keep the countersink concentric with the cylindrical portion of the hole.

3.5 Motivations for Implementing Automation

An extensive amount of work is involved in drilling and countersinking each of the many holes in the wing assembly. This work is physically demanding, often resulting in shoulder or other joint injuries because of the repeated torques that mechanics are exposed to. At the same time, the work must be performed precisely in each of the drilling and countersinking steps so that fasteners fit correctly and distribute their loads as designed. In other words, each hole provides multiple opportunities to make a potentially-costly error. Even in the best case, the time required to perform this work manually represents a significant cost to the company. These factors led Boeing to consider replacing the manual drilling and countersinking operations for joining wing skin panels to spars with automation.

4 Flex Track for Wing Assembly

In an effort to reduce injuries, quality defects, and cost associated with the drilling and countersinking of holes common to wing skin panel assemblies and spars, Boeing decided to implement Flex Track automation to replace the existing manual process on the 777 assembly line. Similar systems had been successfully implemented for other hole drilling applications within the same factory, and only minimal design changes were expected to adapt the equipment to this application.

4.1 Flex Track Equipment for Wing Application

In order to drill the holes common to wing skin panels and spars, the tracks of the Flex Track equipment mount to the surface of the skin panel using vacuum cups. Because of the proximity of the holes to the edges of the skin panel, the machines must drill holes offset from one of the tracks. In the case of the holes common to the rear spar the holes are drilled below the lower track, while they are drilled above the upper track for holes common to the front spar. The image in Figure 5 is taken from an equipment vendor's website and shows a typical Flex Track machine drilling holes common to the upper skin panel and front spar of an unidentified wing.
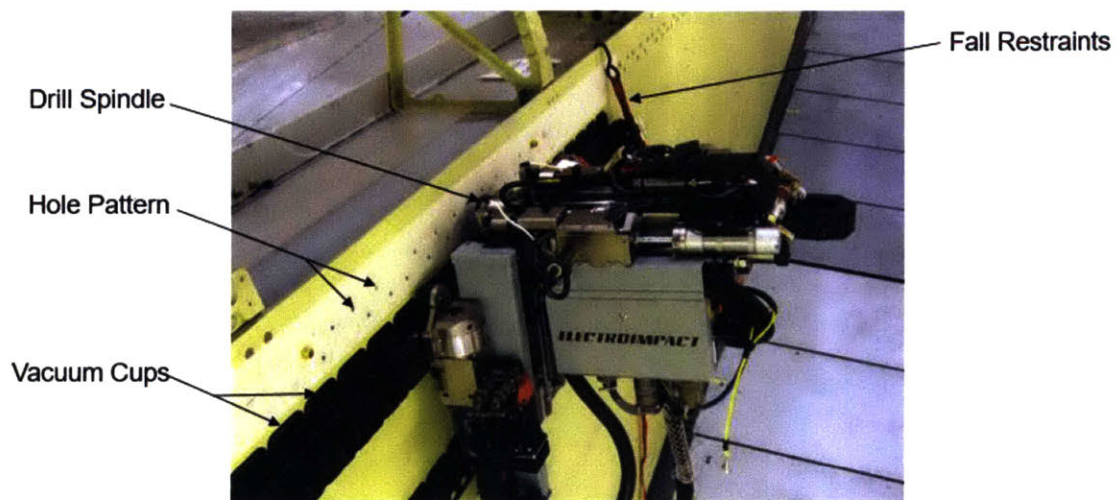

Figure 5: Flex Track machine drilling front spar [12]

Unlike in circumferential applications where the tracks form a closed loop that prevents the carriage of the machine from falling, the wing application requires a secondary form of fall restraint to protect workers and the equipment in the event that the track vacuum system fails. Depending on the part of the wing being drilled, different fall restraint methods are needed because of differences in potential attachment points on the surrounding structures of both the FAJ and the wing itself. In some cases, additional structures must be added to the FAJ to provide an adequate attachment point. With these exceptions, the equipment and process for operating Flex Track are nearly identical to those used in previous applications.

4.2 Segmentation for Automation and Phased Implementation

Given the capabilities of the Flex Track machines that were specified, all but the largest holes common to the skin panels and spars could be drilled and countersunk as long as the machines had reference holes available to orient themselves. Based on process time estimates from the equipment vendor, engineers divided each spar-panel joint into segments of a length that could theoretically be completed by one machine in a shift. Each of these segments is referred to as a media.

Machine programs were then created for each of these segments based on the Computer-Aided Design (CAD) models that indicated the locations of the holes that the machine was to drill. The programs translated the data from the model into detailed instructions for where the machine was to move. They also contained instructions for the speed of drill bit rotation, the rate at which the drill bit was to be fed into the parts, and the depth to plunge into the part in order to create the appropriate size of countersink. Further instructions could also be added to tell an operator when to change drill bits or verify the quality of the holes.

A phased approach was selected for the implementation of Flex Track in wing assembly. One media at a time would be brought online as the corresponding manual work was phased out. This

would allow engineers to focus their efforts on any problems that arose before the next statement of automated work was introduced. It also provided time to develop or acquire the new tools required to safely operate in some of the more challenging locations on the wing.

Before any new media was implemented, the accuracy of the CNC program was verified by replacing the drill bit in a machine with a fine-tipped marker and touching all of the points on the wing skin panel where the program indicated that the holes should be located. This provided an opportunity to catch and correct any errors before they resulted in a costly defect. It also provided an opportunity for engineers to train operators and team leaders in the operation of the equipment and the process flow.

4.3 Drilling with Flex Track

Like the manual drilling process, Flex Track depends on reference holes to locate and orient the hole pattern. Before the machine is ever installed on the wing, reference holes are drilled concentric with the pre-drilled holes on the spar assembly. Tack fasteners are then inserted into each of these reference holes to hold the skin panel tightly against the spar during drilling.

With the tack fasteners in place, the machine can be set up for production. A specialized tool is used to draw a line on the skin panel to provide a reference for where to attach the tracks. A small hoist or crane is then used to lift the machine along with its two track segments into position against the wing. With the tracks held in alignment by one operator, another operator attaches an air supply line to one end of each of the track segments to activate the vacuum cups. At this point, the machine can be fully supported by the vacuum cups on the tracks.

The fall restraint devices specific to the media being set up are then attached to the carriage and tracks, and the hoist or crane is disconnected. Two additional track segments are then attached and aligned to both the top and bottom tracks that were loaded with the machine. The end tracks are then attached to additional air lines.

With the carriage and tracks in place on the wing, the chip vacuum, power cord, and communication cable are all attached to the carriage before the machine is turned on. The operator then installs drill bit corresponding to the size of the first hole to be drilled. The machine carriage is positioned over one of the reference holes and is instructed by the program to use its onboard camera and vision system to find the center point of the hole. Once that point is found, the carriage automatically moves to the adjacent reference hole and finds its center point.

These two points, along with the surface of the skin panel, provide the machine with the information needed to identify the precise location of the drill relative to the skin. The pre-programmed location of each hole is then translated by the controller into rotational distances that the machine's servo motors must turn to position the drill point correctly. When the machine has found the two reference holes and can map the hole center points onto the wing, the carriage moves to center the drill over the location of the first hole.

Upon the operator's instruction, the machine drills the first hole and moves to the side to allow the diameter of the hole and the depth of the countersink to be checked. Despite precise tool preparation, the countersink depth is adjusted manually to reach the nominal dimension using an offset in the controller. The machine then moves to the programmed position of the next hole and drills again. The adjustment of countersink depth is repeated for each hole until the operator is satisfied with the hole quality. The machine is then allowed to drill the remaining holes in this section of wing automatically with pauses at pre-defined intervals to allow for in-process quality checks.

After all of the holes between the first two reference holes have been drilled, the machine moves to the next reference hole and finds its center point before beginning to drill the next set of holes. As the machine drills, the operator uses a manual deburring tool to remove any irregularities from the bottom surfaces of the first set of holes.

When the program reaches a new hole size, the machine stops and waits for the operator to change the drill bit to the appropriate size. Each drill bit is equipped with an RFID chip that allows the machine to verify the size before drilling again. As the machine reaches the end of the three track lengths that were originally installed, it pauses again and cues the operator to move the first two track segments ahead of the machine's path in an operation referred to as a "leapfrog."

This entire sequence repeats itself with intermittent quality checks, drill bit changes, and leapfrogs until the last hole of the media has been drilled. The operator can then begin the cleanup process by removing the drill bit, attaching the crane or hoist to the carriage, removing fall restraints, disconnecting air supply to the tracks, and placing the machine on the storage cart. After deburring the last of the holes, the operator takes all of the equipment to its storage location. The manual cleaning, sealing, and fastener insertion processes follow as described in Section 3.3 (page 16).

5   <u>System Improvement Strategy</u>

When the author first encountered the Flex Track system, approximately half of the 777 wing media had been implemented. Managers and operators familiar with the system noted that the equipment generally operated safely and produced good quality holes, but frequent malfunctions led to significant delays in production. They said that even on the best days, the machines were unable to meet the targeted production rates, and this led to overtime. In general, the system was perceived as more of a problem than an asset.

Because of the inherent complexity of the manufacturing system and the process being studied, a structured approach was needed to identify and address the root causes of problems. This chapter is organized around the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) framework.

5.1 Defining the Problems

The intent of implementing Flex Track automation in this assembly process was to reduce worker injuries, improve quality, and reduce costs associated with the drilling and countersinking of holes while continuing to produce wings at the rate needed to meet customer delivery dates. Based on initial interviews with stakeholders close to the process, it appeared that the primary problem was that the equipment was unreliable, and this led to delays in the production schedule. These delays increased production costs because mechanics had to work overtime to get back on schedule. Further observation of the process revealed additional problems that deserved further analysis.

Although the very nature of the change from manual drilling and countersinking to automation was certain to deliver the intended result in reducing worker injuries caused by repetitive torque, automation such as Flex Track can introduce an entirely new set of hazards in the workplace. Many

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of these potential hazards were addressed in the pre-implementation stages by such measures as fall restraint devices, but some additional hazards were discovered after implementation.

The most severe of these hazards was the presence of pinch points on several media as the machine traveled through particularly tight spaces in the FAJ. In order to avoid this hazard, operators were prohibited from walking behind the machines when they were installed on these media. Since tasks such as leapfrogs and adjustments of fall restraints could require operators to access both sides of the machine in short periods of time, two operators were assigned to these media. Though this measure mitigated the safety problem, it also doubled the labor cost associated with these media.

The hole quality produced by the Flex Track machines was generally very good, but several groups of holes intermittently had problems with deep countersinks. When a countersink goes too deep, the fastener does not fit properly, and the hole must be drilled to a larger size to accept a larger fastener. This type of rework is not difficult, but it can be costly because of the time spent by engineers, mechanics, and inspectors to make sure that the final result does not diminish the safety or performance of the airplane. As a result, this problem would need to be addressed to bring the Flex Track system in line with its quality and cost goals.

As mentioned in initial interviews, machines stopped during production for a variety of reasons. Sometimes components would fail and require maintenance, and other times an error would appear on the controller for unexplained reasons. Since not all of the media had been implemented, there were usually spare machines available that could be used to complete the work if a problem could not be resolved immediately. The result, however, was often a delay that led to overtime. The variety of failures suggested that there were likely several root causes that would have to be addressed.

While failure to complete the drilling of a media on time was typically linked to a problem with a machine, there were two media that occasionally finished late even when there were no notable problems with the machines. This indicated that there was another underlying problem that led to delays, but further study would be required to identify it.

5.2 Measuring Ongoing Performance

Although existing safety and quality systems would quickly alert managers to problems, there was no easy way for managers or engineers to see how the Flex Track system was performing in terms of time, schedule, or equipment reliability. The only information that was used to assess these aspects of performance was word of mouth, which did not provide a consistent or objective view.

The Flex Track equipment contained software that recorded various events or conditions detected by the machine, including the drilling of a hole and various error states. This data was accessed and plotted on a weekly basis to monitor the performance of the system. With this information, the impacts of future changes could be assessed against a baseline, and new opportunities for improvement could potentially be uncovered.

Figure 6 is an example of the plot used to track production time and schedule performance for one media. The lower set of data points represent the time of the first hole drilled on the media on a given day, while the upper set of data points represents the time of the last hole drilled for that media on the same day. The time between the first and last holes represents the total time required to complete the drilling of that media, including any stoppages in production.
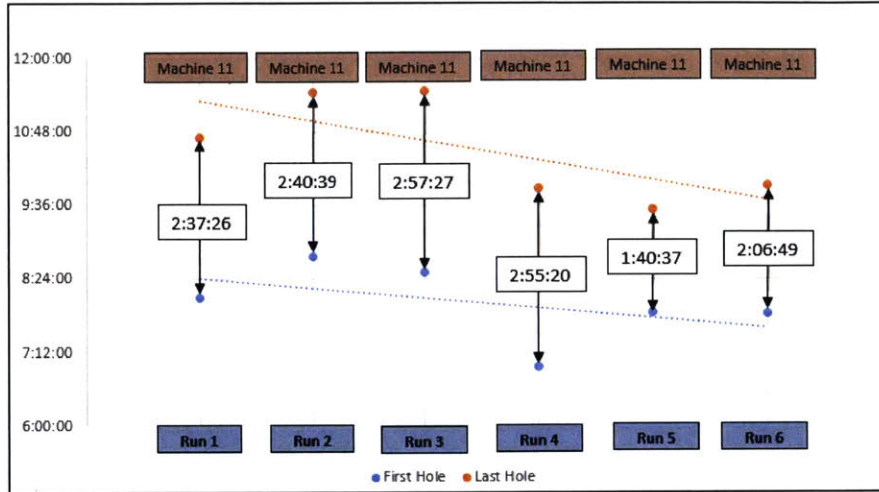
Figure 6: Drilling times and durations for six consecutive production days

Figure 7 is an example of a tool used to track the equipment reliability over the course of a week. Each row of the plot is a timeline of the activity of one of the machines that was in use. The holes drilled by each machine are represented by vertical blue lines, while yellow triangles represent machine errors that stopped production and required intervention by maintenance.

Figure 7: Holes drilled and production-stopping errors recorded by machine

With these tools and the associated data in hand, the performance of the system could be monitored, future changes could be compared to a historical baseline, and known problems could be further analyzed to create a plan for improvement.

5.3 Analyzing the System

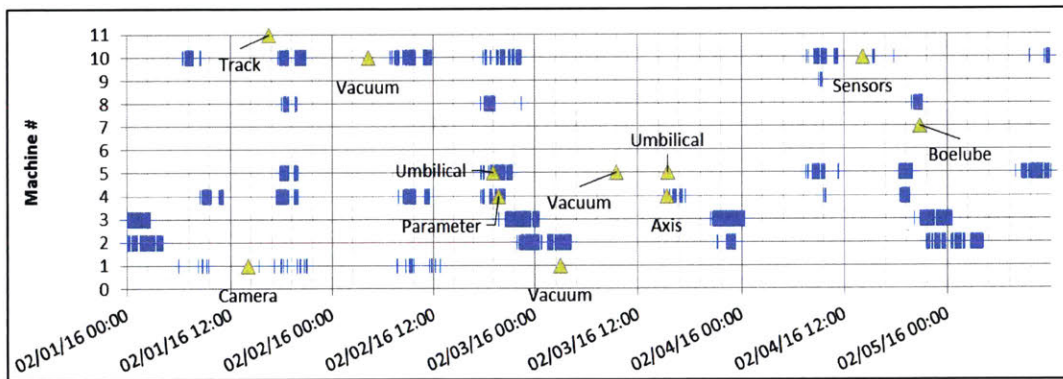With a method in place for measuring ongoing performance, analysis was needed to identify and prioritize potential changes to quickly and sustainably improve the system. The most pressing shortfall in performance was that production times using Flex Track often exceeded the scheduled time, and there were two strategies for improvement that could be used to address this shortfall:

1) Reduce the duration of the process, or

2) Increase the amount of time available for the process.

Either strategy or a combination of the two could be used to improve the on-time completion performance of the system. However, a detailed understanding of the process timeline was needed to identify specific changes that would correspond to these strategies. Time studies were performed for several of the Flex Track jobs to understand what was happening at each moment as the job progressed. Figure 8Figure 8 shows a general process timeline with the automated Flex Track drilling between manual setup and teardown operations. The manual and automated processes are fundamentally different and are treated separately in the analysis that follows.

Figure 8: General process timeline
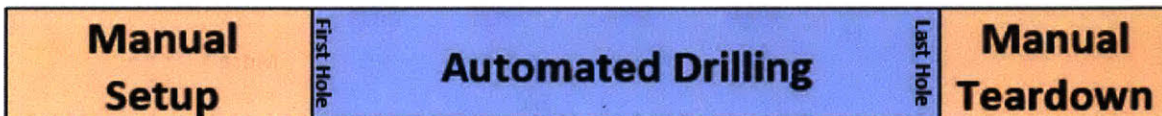
The preparation for Flex Track drilling is typically scheduled to begin at the beginning of a shift of work. This includes all of the reference hole drilling and setup of the equipment. This type of work is manual in nature, similar to the other work that is done in the FAJ, and it can be performed consistently and efficiently by a skilled team. No standard operating procedures were used to

define the roles of different operators during setup, so teams were free to determine their own methods as long as they did not violate any safe operating guidelines.

Through observations of different teams of operators, it was evident that some teams preferred individual setups where each operator was responsible for all tasks from setup to teardown, while other teams preferred to pool all of their operators and execute the collective setup tasks in parallel before individually running the machines for automated drilling. Setup times were recorded and compared for setup operation on right-hand and left-hand wings that involved an identical set of tasks. The right-hand and left-hand operator teams used the individual and pooled setup methods, respectively. Times were measured from the beginning of the first setup task until the first hole was drilled. Figure 9 and Figure 10 show the distributions of setup times normalized to the target time for ten observations of each team.
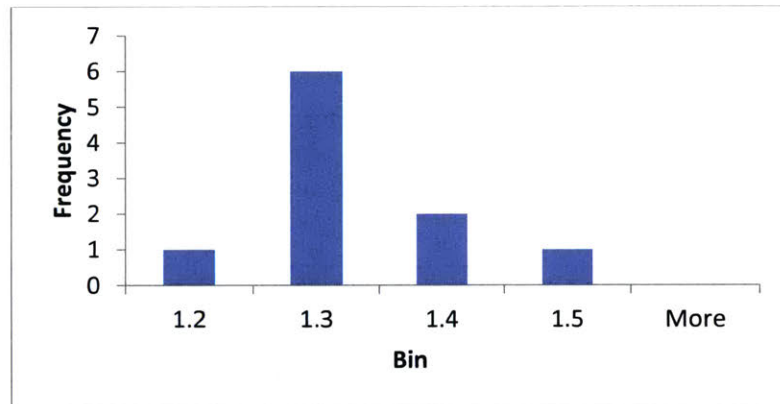
Figure 9: Histogram of normalized setup times for individual method
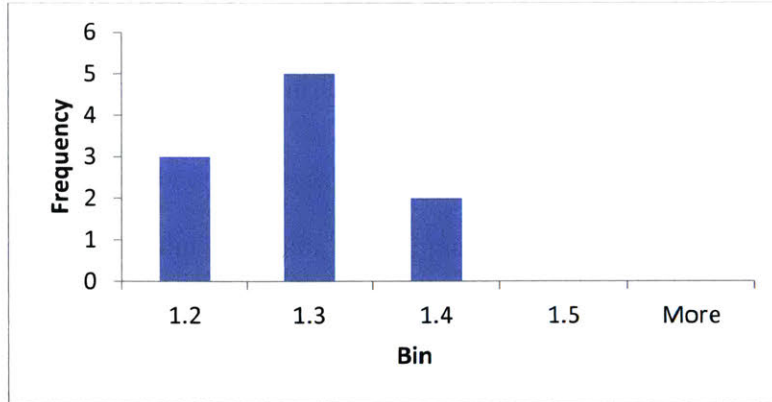
Figure 10: Histogram of normalized setup times for pooled method

These initial observations lead to the hypothesis that the pooled method for setups is more consistent and faster in getting the machines and operators ready for production. Intuitively, this makes sense because any problems faced in a setup can be distributed across the team using the pooled method, taking advantage of the entire group's knowledge and resources. Further, some tasks in the setup operation are better suited for multiple operators, and others are better suited for one operator. Pooling the operators to collectively complete this set of tasks allows a team to allocate the optimal number of operators to each task, while individual setups limit each task to one operator.

Independent of the work methods used by operators, delays in setup most commonly occurred when a piece of the equipment was not in the expected location or was found in a damaged condition. In these cases, valuable production time was spent looking for usable equipment or

waiting for the equipment to be fixed. Rigorous standardization of storage locations, maintenance practices, and communication between shifts could eliminate most of these delays.

Even when such delays were not present, setup times exceeded the targets that were set prior to implementation by at least 14%. Unless significant changes could be made to setups, additional time would need to be allocated to these operations in scheduling.

Like the setup portion of the process, the teardown is manual in nature. Unlike in the case of setup, however, operators know exactly the location and condition of the equipment when they begin. Accordingly, it is the best time to request any maintenance that is needed on the machines and ensure that everything is in the correct location for the equipment's next use. If this were done after every use, very little time would be added to the teardown, and the next operator to use the same equipment would not be subject to one of the primary drivers of variability in the setup.

In the case of teardown, different crews used similar processes for getting the equipment off the wing and to storage locations. Drilling almost always ended at different times for different media, so operators would individually perform the tasks that were safe for an individual, and other operators or team leads would assist with the tasks that required multiple operators. Since the sequence of these tasks was not critical, the help could arrive at almost any time in a 15-minute window and have the same effect. As a result of these factors, teardown times were generally more consistent and did not exhibit the same level of variation from one team to the next.

Figure 11 shows the distribution of teardown times normalized to the target time for one rear-spar media. Actual durations of teardowns on front spar media were similar but more difficult to measure because other jobs were often performed while operators waited for assistance. The times almost always met or beat targets for duration and exhibited a relatively small amount of variation across operators and teams.
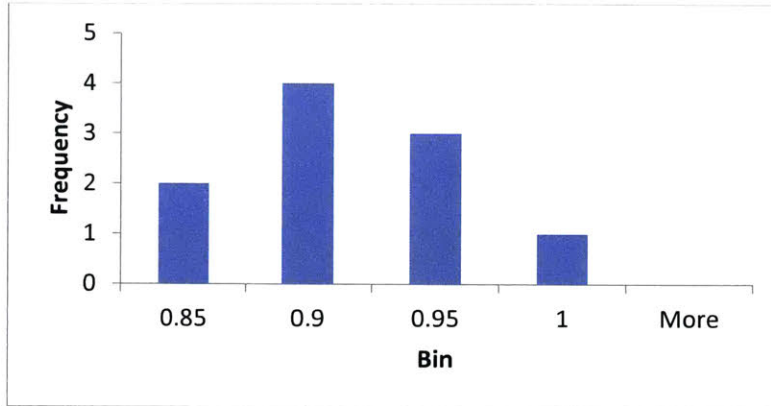
Figure 11: Histogram of normalized teardown times for one rear spar media

The automated drilling portion of the process begins as soon as the setup ends and is typically run by one operator unless two operators are mandated for safety reasons. Automated drilling is more complex than setup or teardown because its performance depends on the actions of both the machine and the operator. Ultimately, the task that must be performed is the drilling and countersinking of holes on the wing, and the job does not end until all of the holes are drilled. Accordingly, any pause or delay in the hole-making process is not adding value to the product. To easily identify and diagnose delays, time study data was coupled with the machine log data to generate graphical representations of the process such as that shown in Figure 12.

Figure 12: Graphical analysis of production delays

These graphs were a useful tool when discussing potential improvements because they very clearly highlighted the times when a mach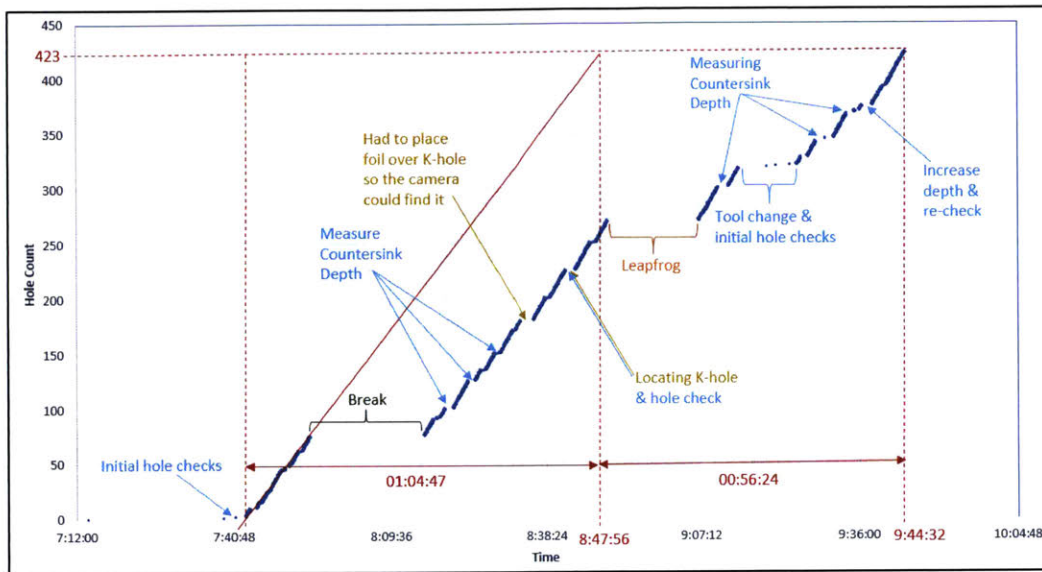ine was not adding value by drilling holes. Any horizontal gap where no holes were drilled or any reduction in the slope of the graph as production slowed could be targeted. The bigger the delay, the more improvement could be derived from its elimination. From Figure 12 alone, the following questions could be asked of the implementation team to look for improvement opportunities:

1) Can leapfrogs be reduced, eliminated, or made faster?

2) Can operator breaks be staggered so that machines can keep running?

3) Can hole checks take place without the machine stopping?

4) Can delays associated with tool changes be reduced?

5) Can the reliability or speed of finding reference holes be improved?

Figure 12 reflects the normal progression of the Flex Track drilling process without any significant machine errors. Some such charts, however, showed lengthy delays when a machine stopped working correctly and maintenance technicians had to be called to fix the problem. In other

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cases, the problem could not be fixed without removing the machine from the wing, meaning that a new machine had to be retrieved and set up to continue drilling.

While the questions proposed above reflect the potential for process improvements that could reduce the process time on a daily basis, machine errors represent a significant source of variability in the process duration. With various error conditions and uncertain response time from maintenance technicians, a single error could increase the drilling time of one media by anywhere from 5% to 35%. Furthermore, multiple errors could occur on the same media on the same day, making on-time completion all but impossible. Although manual drilling could theoretically be used to supplement the work of a machine that falls behind schedule, the potential risks of working near or beneath suspended tracks and machines outweigh any benefits.

In analyzing the delays in Flex Track drilling, it is important to differentiate between random variation in operating time and delays resulting from machine errors. By understanding the magnitude and frequency of the different sources of delay, the appropriate priorities can be determined for addressing each source. Figure 13 shows the time distribution for drilling one media, while Figure 14 represents the same data with the effects of recorded machine errors removed. In both figures, the drilling time is normalized to the target duration.
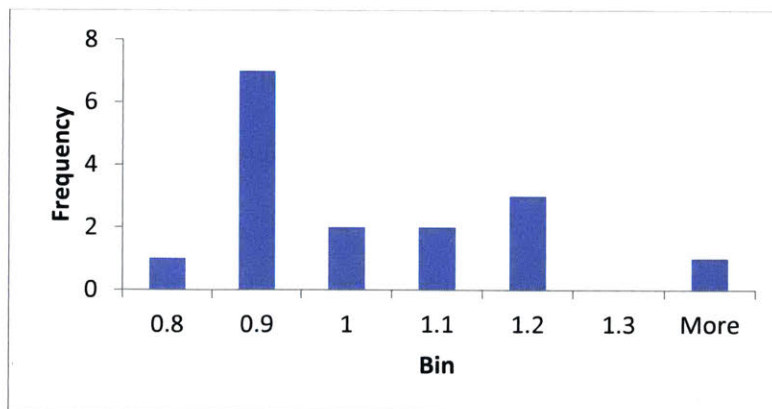

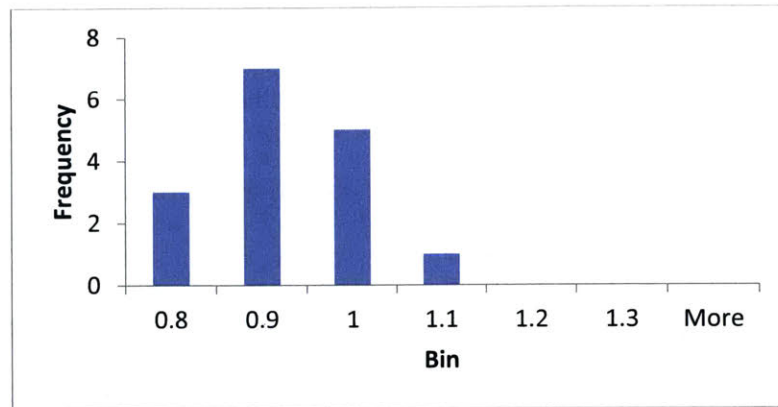Figure 13: Histogram of normalized drill times for one media

Figure 14: Histogram of normalized drill times with recorded machine errors removed

As can be seen in the figures above, the operating times without machine errors beat target times, while machine errors extend the right tail of the time distribution to frequently exceed target times. Therefore, the single greatest opportunity to improve the frequency with which the machines meet their targets is to reduce the frequency and severity of machine errors. However, such errors would be difficult to eliminate immediately, so continued efforts to reduce process time should also be used to mitigate the effects of the errors.

5.4 Plan for Improving Performance to Objectives

Analysis of the various parts of the Flex Track process provided an understanding of the dynamics of the process time in the manual and automated segments independently. Several areas for improvement were identified, but prioritization was needed to understand where time and other resources should be focused.

The most pressing problem that needed to be addressed was the frequency and extent to which Flex Track operations exceeded their scheduled duration. Any time that a Flex Track process was not completed on time, high costs were incurred in the form of overtime labor for Flex Track operators and for mechanics that had to wait for Flex Track to finish before beginning their work.

The overtime cost when one media exceeded the target time was nearly identical to the overtime cost when all of the media exceeded the target time because all of the holes must be drilled before cleaning, sealing, and fastener insertion could begin.

As a result, the target for minimizing cost is to complete all of the media within the targeted duration as frequently as possible and to minimize the maximum duration among all media if the target is exceeded. In all cases, the focus is on the worst-performing media. Because the setup, drilling, and teardown times of all of the media are subject to high levels of variability, any of the media could be the worst-performing for any given shift.

In order to estimate the long-run frequency and extent of schedule overruns, a method was needed to infer the behavior of the complete system of Flex Track machines based on the baseline data that had been collected. Data was available for the durations of setups and teardowns in different areas of the wing, as well as for the duration of the automated drilling of each media. As seen in Figure 13, the durations of certain components of the Flex Track process do not likely follow an underlying normal distribution, and the manual portions of the process are likely to follow different distributions than the automated portions. Fitting a probability distribution to the data in order to make statistical inferences would require heavy assumptions that would add uncertainty to the estimates.

While observing maximum times for each media would provide an alternative analysis to determine whether or not an overrun might occur, the existing data would show that this outcome is possible for any media. The many possible combinations of setup time, drilling time, and teardown time could result in a wide range of times to complete each media on a given shift, including times that exceed the targets. In order to consider the full range of possible combinations, a simulation was designed that randomly pulled a setup time, drilling time, and a teardown time for each media from the appropriate baseline datasets and added them together to create a simulated

media time for the shift. Of all of the media simulated, the one with the maximum duration was compared with the target time to determine whether a delay would occur and, if so, to what extent the time exceeded the target. Figure *15* illustrates the structure of the simulation in a simplified case that only uses three media per shift.
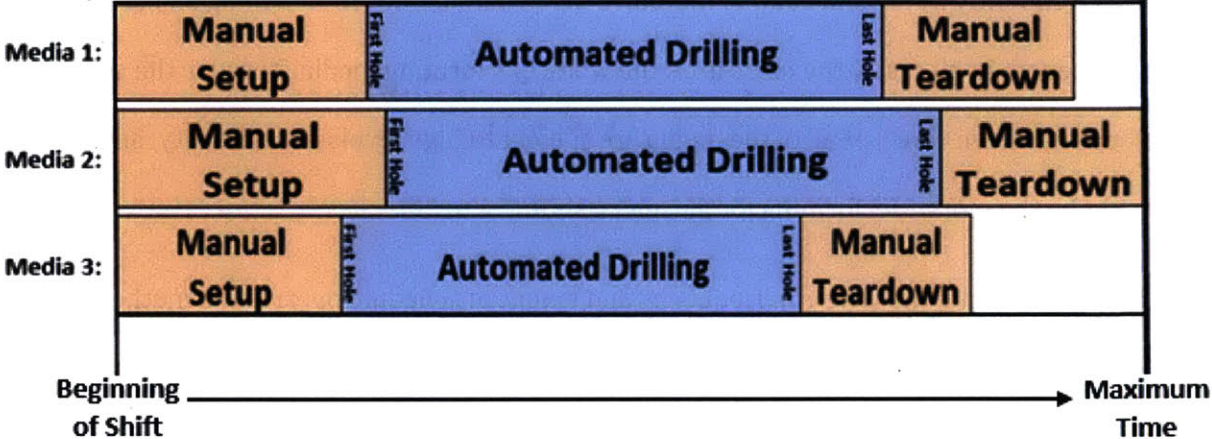

Figure 15: Simplified illustration of simulated Flex Track shift

In the case of Figure *15*, Media 2 had the longest duration for the shift. The maximum time, which would be recorded at the end of the teardown process for Media 2, would then be compared to the target time to determine how well the system performed to schedule.

The same random sampling from the data was repeated 500 times in the simulation to generate a distribution of maximum Flex Track process times. Because the data was randomly sampled for each simulated shift, the distribution generated by the simulation approximates the long-term performance of the system under the assumption that the process continues to run exactly as it ran when the baseline data was collected.

The first simulation used the raw baseline data from time studies and the machines' automated data recording system. The normalized maximum time distribution for this simulation is represented by Figure 16. In 187 of the 500 simulated wings, the normalized maximum time was above one, meaning that at least one of the media exceeded its target 37.4% of the time. Among

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those times that exceeded the target, the average overrun was 9.9% with a maximum overrun of 20.7%.
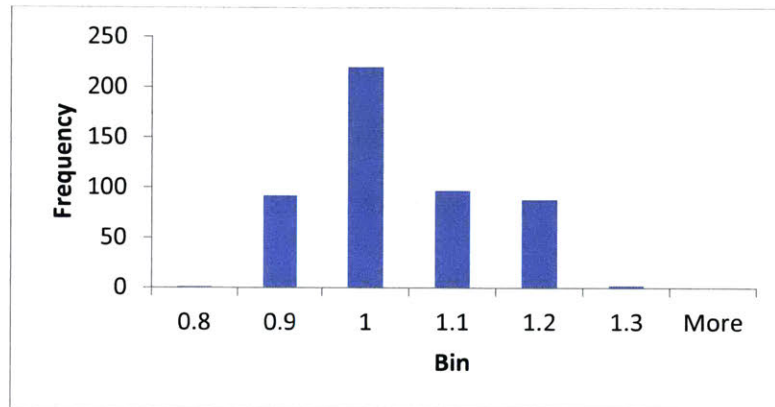
Figure 16: Simulated full process times under current conditions

To assess the potential benefits of standardizing setup and teardown procedures to reflect best practices, a second simulation was run replacing the actual setup and teardown data with a constant value that was set to the historical minimum duration. The results of this simulation are shown in Figure 17. In this case, the worst-performing media exceeded its target in 121 of 500 simulations, or 24.2% of the time. Of the times that exceeded the target, the average overrun was 10.6%, and the maximum was 16.9% beyond the target.
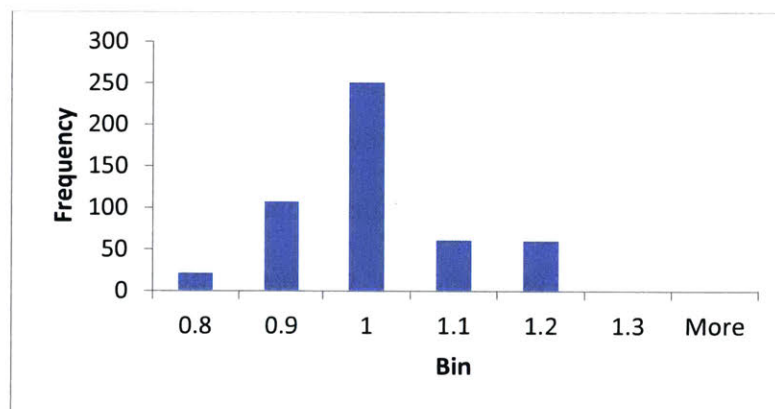

Figure 17: Simulated full process times with minimum setup and teardown times

The potential impact of increasing the time available for the process by thirty minutes was then assessed by increasing the target time use for normalizing the results and re-running the simulation. This additional time buffer could be added to the process by rescheduling the work around Flex Track to start earlier, finish later, or bring in additional operators so that machines can continue to run through lunch breaks. Figure 18 shows the distribution of normalized maximum durations under this scenario. At least one media exceeds its target time in 97 of the 500 simulated wings, or 19.4% of the time. Further, the magnitude of the time overruns decreases when the buffer is applied, with an average of 4.8% and a maximum of 9.9%.
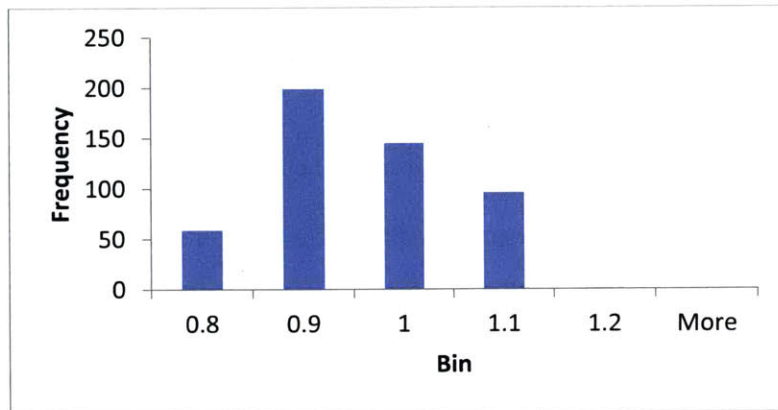
Figure 18: Simulated full process times with 30 minute buffer

In the final simulated case, the potential impact that could be achieved by eliminating machine errors was evaluated by sampling from drilling times that had been adjusted to remove the effects of recorded machine errors. Figure 19 shows the normalized maximum time distribution for this case. Since no data points fall above a normalized time of one, a process performing under these parameters would almost never delay the start of subsequent processes.

Figure 19: Simulated full process times with no machine errors

Clearly, eliminating machine errors is the most direct way to make sure that the process always can finish on time. However, errors and delays of many varieties should be expected early after the implementation of new equipment, and eliminating such errors can require significant time and effort. Increasing the amount of time available for each process by thirty minutes, on the other hand, may only require small changes in the work schedule and demonstrates the potential to prevent almost half of the schedule overruns.

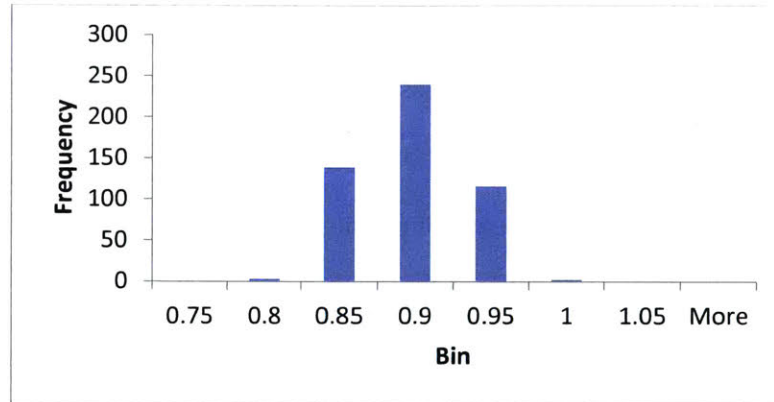The strategy of increasing the available process time creates a time buffer to help accommodate the variability in the process, which is largely driven by the machine errors in the case of Flex Track. Since changing worker schedules can be disruptive, and additional time may require costly overtime, increasing time buffer should be seen as a temporary measure to mitigate the effects of the variability in the process. As the root causes of machine errors are addressed and variability in the process decreases, the extra buffer should be reassessed with the intent of reducing and eventually removing it. While thirty minutes of buffer time was used as a basis for evaluating this strategy, the actual buffer time should be selected to minimize the total cost.

With the general strategy of increasing buffer time in the short run and decreasing machine errors in the long run, a detailed prioritization of projects was needed. Various stakeholders and decision makers were convened to assess each potential improvement for impact and

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changeability. Any change that could quickly improve the performance of the system was given a high priority. Lower priority was given to changes that would have a lesser impact on performance, a lower probability of success, or a longer time horizon for execution. Ultimately, the strategy of increasing the time buffer of the process was not pursued because adding and later removing additional time in the schedule was considered too disruptive to the workforce.

Three improvements that could be quickly implemented and were expected to reduce the frequency of some of the most-prevalent machine errors were selected as top priorities:

1. Improve protection and handling of umbilical cables to reduce communication errors between the Flex Track controller and carriage. This involved the implementation of devices to protect the multi-pin connectors at the ends of the cables when they were not in use, as well as increasing operator awareness of problems that resulted from damage to the cables.

2. Refine the tool change procedure to prevent damage to the Z-axis scale, which allows the machine to accurately determine the depth of the drill bit. Tool changes on the Flex Track machines require the operators to adjust a setscrew with a wrench. The original procedure did not define the rotational position of the tool for a tool change. Some positions created a high risk for inadvertent contact with the Z-axis scale, which sometimes resulted in damage that made the machine lose track of the drill bit depth. Under the new procedure, the tool was rotated to an orientation that prevented contact between the wrench and the scale.

3. Upgrade the control system's uninterruptable power supply (UPS) to prevent startup errors after weekends or other long periods without a connection to external power. Errors were more frequent when machines were used after remaining disconnected from power for several days. It was determined that these errors resulted from loss of power to certain parts of the controller that should have received power from the UPS during these periods. An upgraded power supply was specified to prevent these errors.

With these improvements largely implemented, new data was taken to assess the drilling durations for ten wings. For consistency with the previous analysis, the observed drilling times were sampled to reproduce the 500-wing simulation in order to estimate the expected frequency of time overruns under the new conditions with the improvements in place. The distribution of maximum times is shown in Figure *20*. Of the 500 simulated wings, at least one media exceeded the target time on 88 occasions, or 17.6% of the time. Among those that exceeded the target time, the average overrun was 3.8% with a maximum overrun of 7.3%.
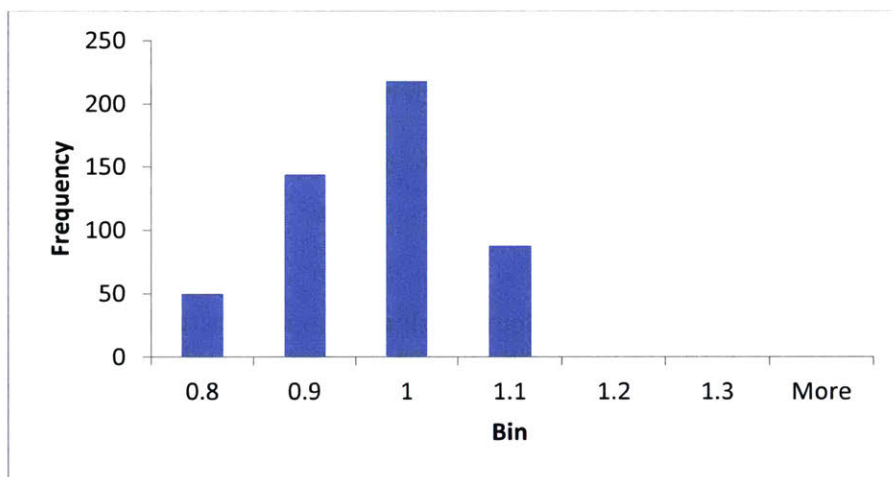
Figure 20: Simulated maximum time distribution after changes were implemented

This represents a significant improvement in performance when compared with the baseline case. The improvement in the simulation is a result of the improved performance of the Flex Track equipment after the changes were implemented. Averaging across all of the media measured, the average drilling time decreased by 5.9% as compared with the baseline performance, while the maximum drilling times decreased by 10.0%.

Despite this measurable improvement in performance, not all machine errors had been eliminated, and there were still instances of time overruns in the Flex Track process. Further changes were in process to target the root causes of these errors, but these changes would not take full effect until after this research project was concluded.

5.5 Maintaining Process Control

Although the process still required improvement before it could be stabilized, it is useful to consider strategies that could be used to monitor and maintain the process in a stable state once the final changes were made. Once the process reaches its targets or any remaining opportunities for improvement are prohibitively costly, the priority of the implementation team should be to ensure that the process performance does not deteriorate. At this stage, the frequencies of known delays or quality defects have been established and deemed acceptable in light of the cost required to eliminate them or further reduce their frequency. New baseline data should be used to characterize the distribution of process times for each media once the final major change has been implemented, and a system should be implemented to detect any shifts in the process that would indicate that it is no longer functioning as intended.

Control charts are commonly used in manufacturing to monitor critical dimensions of parts so that shifts in the process can be quickly identified. A control chart uses statistical methods to compare actual process performance to the expected performance, which is modeled based on historical data. When a change occurs and is detected by the control chart, engineers can look for the root cause of the change and correct any problems so that the system can return to normal operation. This same strategy could also be applied to monitoring the time required to complete the drilling of each Flex Track media.

Many control chart models depend on the assumption that the data used is sampled from a process with an underlying normal distribution. Using the means of samples of n=4 or greater can often allow these models to work with other distributions because the distribution of the sample means may be approximated as a normal distribution [13]. In the case of Flex Track run times, the data does not necessarily follow a normal distribution. Figure 21 is a normal probability plot of drill times for one Flex Track media, which shows that the drill times do not follow a normal

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distribution. Figure 22 is an identical plot for the same data adjusted to remove the effects of machine errors.

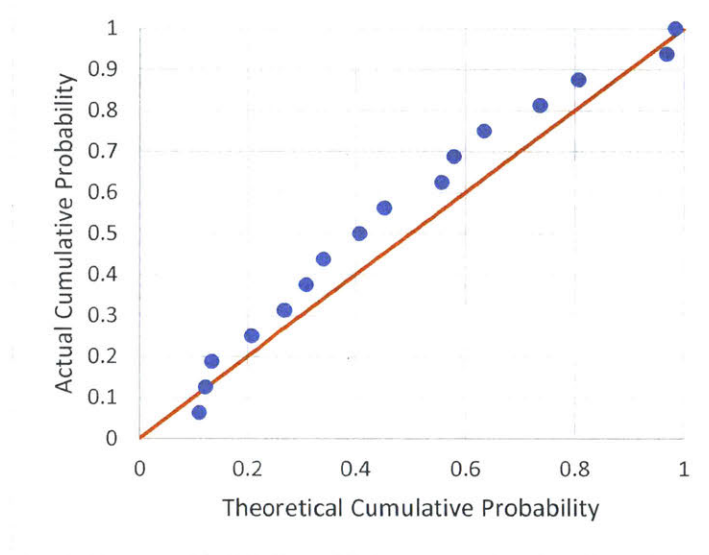Figure 21: Normal probability plot of drill times for one media. If the underlying data were normally distributed, the blue dots would follow the orange line.
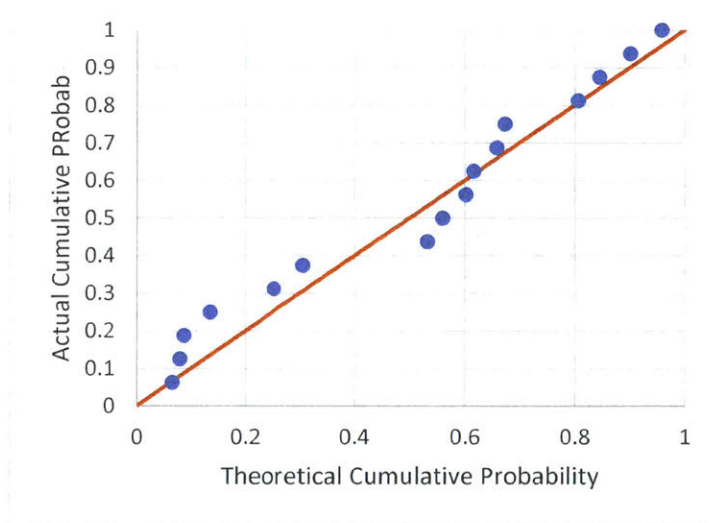

Figure 22: Normal probability plot for drill times adjusted for machine errors

The poor fit of the data to a normal distribution is not surprising since the data was taken when changes were still being made to the process and equipment, meaning that it was not in a

state of statistical control. Even after the process is stabilized, however, it is critical to recognize that the underlying data may not be distributed normally, and this should be checked before building a control chart that uses this assumption.

If normality cannot be assumed for the drilling time distribution, a larger sample size could be considered for creating control charts. However, waiting to observe the process time for four or more consecutive wings before recognizing a deterioration in performance would not be acceptable because of the low production rate and high cost associated with exceeding target times. A method for monitoring the process is needed that is both sensitive to a single extreme deviation from the target and to repeated smaller deviations.

As a result, a cumulative sum control chart is recommended for this application. A cumulative sum control chart keeps a running total of the measured quantity's deviation from the process mean. Over time, the values will go up and down but should not stray far from zero because the mean deviation from the process mean is zero. If the mean shifts, however, this becomes evident because the cumulative sum will quickly move in the direction of the mean shift. Upper and lower limits can be established as signals that a likely change in the process should be investigated. An example of a cumulative sum control chart is shown in Figure 23, which applies this method to the adjusted drill time values plotted in Figure 22.
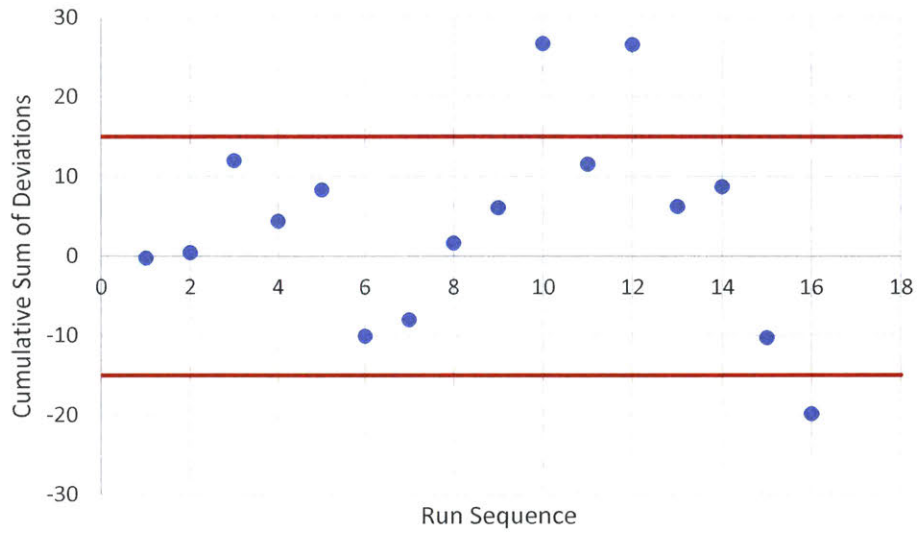
Figure 23: Cumulative sum control chart example

In this example, alarms would occur at run numbers 10, 12, and 16 because observed times fall outside of the established limits. In practice, engineers should investigate the cause of each alarm condition and determine what corrective action should be taken. It is likely practical to reset the cumulative sum to zero following an alarm. If the cumulative sum frequently alarms on the lower limit, the conditions and practices that lead to these alarms should be studied to see if improved work methods are being used that could be extended to other media. When this case arises, the parameters of the control chart may need to be adjusted to reflect a lower mean time.

5.6 Chapter Summary

This chapter outlined the system improvement strategy that was initiated when the author began working with Flex Track. Problems with the system were defined, and it was confirmed that process time overruns were the most critical shortfall of the system. Data was collected and used to measure various aspects of the process, as well as to provide the basis of the analysis used to prioritize changes that would be made to the system. These changes were targeted toward bringing

the process time under control, and initial data indicated an improvement in on-time performance compared with the baseline. Despite improvements, the system still showed signs that machine errors were leading to occasional delays in the process. Finally, a method for monitoring the process was proposed to quickly recognize changes to the process time once all of the changes were implemented.

6   Conclusions and Recommendations

The previous chapters focused on the implementation of automation in an existing production system and demonstrated some of the analytical tools that can improve decision-making in such situations. This chapter presents some final conclusions and recommendations that come from this analysis, including potential areas for future research.

6.1 Time and Resources Needed for Implementation

Implementation of automation takes time. The more perfectly the system needs to perform, the longer it takes to bring it up to its targeted level of performance. In an existing production system, where processes have already stabilized and matured, replacing a manual process with automation can introduce new challenges that must be accounted for.

When automation is introduced at the inception of a new assembly line, all of the processes are brought up to speed simultaneously. In aerospace manufacturing, the majority of the improvement in all of these processes usually takes place during a low-rate initial production (LRIP) phase, which is specifically intended to allow processes to stabilize before beginning full-rate production. The low production rate gives engineers and operator teams the time needed to fully learn the systems that they are working with and to address any problems that are encountered in the production of one unit before running the process again. Further, the low production rate allows each process to have a large time buffer to recover from any delays that occur without interfering with subsequent processes.

In the case of replacing a manual process in an already-stabilized manufacturing system, the production rate is likely far faster than would be experience in LRIP. This means that any problems that must be addressed with the system must be addressed more quickly, or they will impact the production of more units. Further, there is less time available to buffer the new process, so the potential negative impact of any delays is much higher, and engineers have less time to investigate

problems that arise. The implementation process is therefore more challenging on two fronts: the urgency of improvement is greater, and the production time needed to bring about the needed improvements is diminished. As a result, more time and resources are likely needed from the supporting engineering teams until the process is stabilized.

Improvement in the productivity of a manufacturing process is often modeled using a logarithmic learning curve. This model predicts rapid improvement early with a diminishing rate of improvement as the process matures. This rate of improvement applies to all of the processes in a manufacturing system and is typically mirrored by increases in production rate as the time needed to troubleshoot and buffer delays diminishes. If the time buffers available and time buffers required to prevent a process from overrunning its schedule are modeled to follow logarithmic learning curves as shown in Figure 24 and Figure 25, it is easy to see how implementing a process in a mature production system might prove to be more difficult.
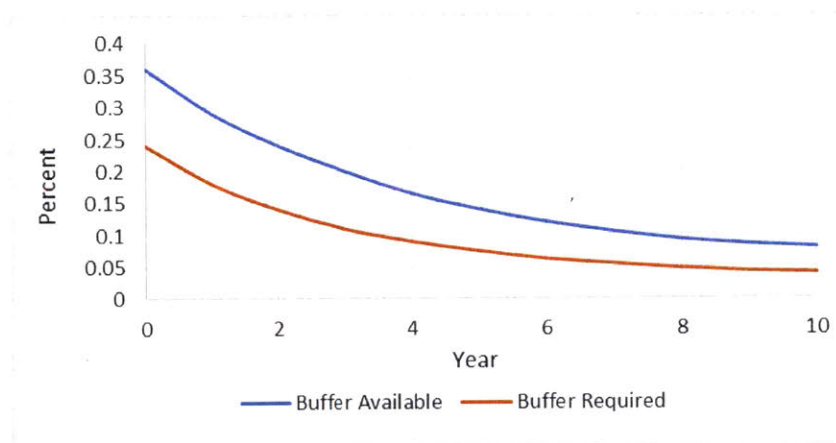

Figure 24: Time buffers for a process implemented concurrently with a new production line
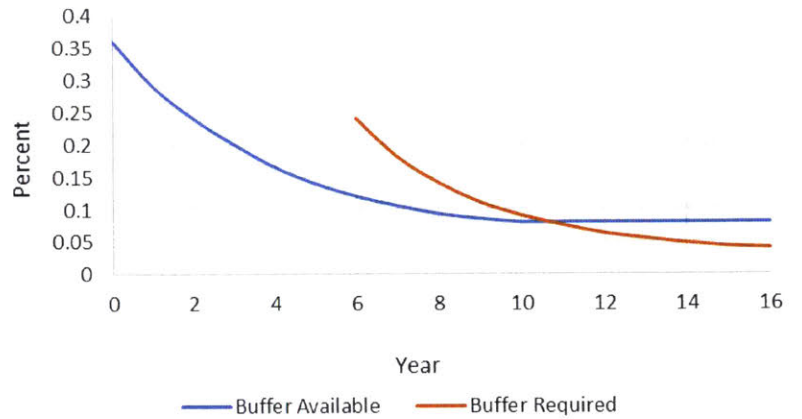
Figure 25: Time buffers for a process implemented in a mature production line

Although the values used in these models are purely theoretical, they clearly illustrate the challenge that is faced when new automation is introduced into a mature production system. Unless efforts are made to accelerate the progress down the learning curve and increase the buffer for the new process, it is likely to disrupt the surrounding production system until the process can be stabilized. Accelerating the progress down the learning curve is achieved with more engineering and management resources focused on the process in the early stages of implementation, while increasing buffers requires creative and flexible scheduling that may increase labor costs in the short term.

6.2 Automation Can Reduce Existing Buffers

Another important consideration when implementing automation to replace a manual process is that some buffers that are used in a manual process may not be available for the automated process. Buffers are used to maintain stable production despite the presence of variability, and there are only three types of buffers that can be used in any manufacturing system: inventory, time, and capacity [14].

Inventory buffers are not practical for an aircraft assembly line because of the size and cost of each unit. Even if storage space were available for spare wing assemblies, the capital required to build up such inventory would likely find better uses elsewhere. This leaves time and capacity buffers as the only viable options for maintaining a stable production rate.

Time buffers are discussed extensively in the previous section and are applicable to any process on the assembly line because each part the production system is driven by a tightly-defined schedule. A time buffer in the schedule for one process allows the process to be completed without interfering with subsequent processes as long as the total delay time is less than the buffer time. In cases where the buffer time significantly exceeds the delay time, the process simply finishes early, and other processes can begin as scheduled. The cost of adding time buffers is that the schedule must account for the buffer time, resulting in a longer scheduled flow time.

Capacity buffers, on the other hand, require that extra capacity be deployed in situations when a delay occurs. In the case of manual labor, additional mechanics can be pooled across a wide range of the processes in a production system and can be assigned to help complete work that falls behind schedule. Automated systems do not have this flexibility because they are typically built for one specific purpose, and the job that they perform is defined long before any delays materialize. For example, a Flex Track machine that falls behind schedule on a given day of production cannot be assisted by another machine to finish on time because each machine is tasked with drilling a fixed set of holes, and no space is available for two or more machines to work on this set of holes simultaneously. In the long run, the work of the machines could be subdivided into smaller media that could be drilled by more machines. This additional capacity, however, would have to be used for every wing and could not be flexibly deployed because of the same space constraints that currently prevent other machines from assisting a machine that falls behind.

When automation is implemented in place of a manual process, the ability to leverage capacity buffers is removed. Manual labor is highly flexible and can be deployed to a wide range of processes to accommodate the variability in the production system. While automation may be more consistent in the long run, it is subject to many possible delays when first implemented, and the only available buffer is likely to be time.

6.3 Build in Flexibility to Allow Rapid Change

When a new automated system is first implemented, it is difficult to predict how the system will perform in the context of a real production environment. It is also given that changes will be required to optimize the performance of the system once it is put in place. Successful implementation requires that engineers and managers have the flexibility needed to bring about those changes quickly.

Regardless of initial performance estimates, the true performance of the system should dictate the course of action once the system is in use. This requires constant measurement and evaluation of performance to inform the decisions about how to best improve the system. Further, once the path to improvement has been established, flexibility is needed to quickly execute the targeted changes so that the performance can be re-evaluated and the next steps to improvement can be determined. This flexibility should be built into the system before it is implemented.

Building in flexibility means ensuring that the resources are in place to make lasting changes to the equipment and process while simultaneously fulfilling the needs of production on a daily basis. Doing so in a fast-moving production environment requires more effort and resources from supporting maintenance technicians and engineers than would be required if the system were implemented in a newer, lower-rate environment. It also requires the capability to quickly develop new machine programs and production schedules so that machine workloads and buffers can be

configured in such a way as to minimize disruptions to surrounding processes without incurring excessive cost.

Future implementations may benefit from a phased introduction approach in which one machine is implemented before any of the others are built. Any improvements that are needed to the original machine can then be incorporated into the original builds of the other machines, reducing the costs of upgrades. Furthermore, such an approach would allow engineers to develop accurate estimates of the process time before determining the number of machines required or establishing schedules.

6.4 Develop Organizational Competencies

As automation technology advances and low-cost competitors continue to emerge, automated systems are likely to become more pervasive in all parts of the aircraft production system. This shift in the manufacturing technology used in aircraft production requires new competencies at all levels of the organization and across many functional areas.

In some contexts, such as the machining of individual components, lessons derived from other industries are applicable and can be quickly applied to improve the performance of similar systems in the aerospace industry. On the aircraft assembly line, both the production system and the applicable automated systems are highly-specialized for their purpose. Because there are fewer examples to build on, successfully implementing automation in such contexts still requires innovative solutions to a wide range of challenges. As more automation is introduced on the assembly line, proven solutions will emerge for addressing many of these challenges.

Even as the technological challenges are addressed for assembly automation, it is critical to keep in mind that a system capable of precisely executing a manufacturing process is not enough to guarantee success. The automated system must be integrated into the surrounding production system before it provides value. This means that equipment storage, maintenance, and scheduling

must be appropriate for the specific needs of the equipment and process. These tasks require that front-line employees, engineers, and managers in a wide range of functional areas fully understand the implications that the automated system have on their jobs. Even in higher levels of management, an understanding of automation is critical so that the appropriate resources can be allocated when and where they are needed.

Another key competency that will contribute to the success of future is the ability to determine the appropriate applications for automation. Automation is not always the best answer when seeking to reduce labor costs. There are many situations where better results could be achieved through an improved manual process. Determining when and where to implement automation is facilitated by considering a wide range of options for each process and understanding the overall impact of each option. As more automation is implemented in different contexts, a better understanding of the impacts of future proposals can be developed. As a result, even automation projects that do not provide the optimal return on investment in the short run may be a good idea if the true goal is to improve organizational competency in automation.

6.5 Opportunities for Future Research

Automation is finding its way into aircraft assembly lines at an increasing rate, and each new implementation provides an opportunity to learn and improve the value that these systems deliver. Continued research focusing on automation in this industry is a key component of this learning. In particular, the following areas of research are likely to yield significant benefits to aircraft manufacturers as they continue to pursue automation projects:

- Simulation of automated systems to predict and improve performance prior to implementation;
- Advanced production system modeling to predict interactions between automation and surrounding processes;

- Design for manufacturing and automation, with a potential to evolve into concurrent product and manufacturing system design;

- Leveraging machine data-collection capabilities for predictive maintenance.

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