

Quantifying the Business Case for Aerospace Assembly Automation

by
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B.S. Mechanical Engineering, University of Auckland, 2010

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

Master of Business Administration
and
Master of Science in Mechanical Engineering

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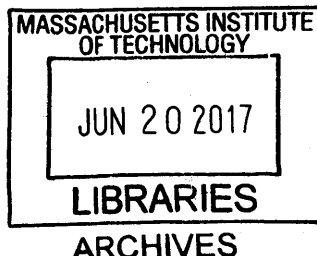
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Abstract

As aerospace Original Equipment Manufacturer's (OEM's) order backlogs soar to between six to ten years and growing, the community sees automation as vital to increasing throughput. Yet the community seems divided on the quantifiable financial benefits. While automation in aerospace assembly dates back to 1937, there is little substantive research on quantifying its business case. This thesis develops a financial model that predicts the benefit of introducing automation into an OEM's manual assembly line. The hypothesis of this project is that there is, in fact, a quantifiable benefit to implementing assembly automation into a current manual assembly process. Based on an initial automation capital investment, the financial model calculates the Net Present Value (NPV) of an aerospace automation project given various OEM production inputs such as: the annual production schedule, learning curve metrics, labor hour savings through automation, rework, health & safety metrics, and automation operating and downtime costs.

A current program was used as a case study against the financial model. One significant finding is the effect production learning has on the labor hours saved from automation—introduced in this thesis as the 'Efficiency Factor'. Based on the OEM's conservative production data and an initial automation investment of \$12M the NPV for the project is about \$16M for the firm order (600 ship sets) and about \$27M for the entire program (2000 ship sets).

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Glossary of Terms

| | |
|---------------------------|---|
| Assembly Datum | A theoretically exact geometric reference that ensures components are assembled correctly. |
| Bullwhip Effect | A phenomenon of increasing volatility of inventory as a result of changing customer demand as one moves further up the supply chain. |
| Cleco | Temporary fastener commonly used to temporarily fasten aircraft skin to the underlying structure before permanent fasteners are installed. |
| Condition of Supply (CoS) | The condition or level of fabrication of parts received from suppliers. Increasing the CoS implies suppliers complete more of the fabrication whereas decreasing the CoS brings more fabrication in house to be performed by the OEM. |
| Determinate Assembly (DA) | Geometric references on assembly parts, such as pre-drilled holes, that are used as assembly datums to aid part alignment during assembly. |
| Drill Plates | Metal, often steel, hole templates used by mechanics to quickly and accurately align hole patterns for drilling. |
| End Effector | A mechanical device attached to the end of a robotic arm, which interacts with the work piece. |
| Gemba | A Japanese term for 'the real place' and means to go and see what is actually happening instead of just talking about it or trying to recall from memory. |
| Metrology | System of measurement. For the purposes of this paper it |

involves vision systems providing measurement feedback to the automation to account for a stack up of tolerances or part misalignments.

| | |
|------------------------------------|--|
| Nominal Fastener | A specific fastener with its part number called out in an engineering specification or drawing. |
| Production Planning Document (PPD) | An assembly plan document from production planning that lays out the standard assembly process with time estimates to assemble ship set 100. |
| Reach Study | A study where every fastener is assessed on its applicability to automation and whether the current automation design can reach each fastener. |
| Real Option | A choice regarding an investment, made available to an organization at some later date when more information is available to aid the decision. |
| Ship Set | The n^{th} unit (aircraft, fuselage, etc.) of production, i.e. Ship Set 100 is the 100 th unit of production. |
| T100 | Industry jargon for the 100 th Ship Set. This is often the ship set that production planners use to estimate assembly times for their PPDs. |
| Takt Time | The maximum time required between units of production to satisfy demand. |
| Tolerance | Permissible limits of variation in part geometry specified in an engineering drawing. |
| Tolerance Stack-Up | The cumulative effect of part tolerances in an assembly. |

Acronyms

| | |
|-----|---|
| ACT | Standard Automation Cycle Time |
| APH | Actual Production Hours that are available each year. |
| AX | Assembly Category |
| CAD | Computer Aided Design |
| CNC | Computer numerical control |
| CT | Cycle Time |
| DC | Direct Cost |
| ECN | Engineering Change Notice |
| ISS | Implementation Ship Set where automation is installed |
| ITI | Initial Tooling Investment |
| LC | Labor Costs |
| LR | Labor Rate |
| MC | Manufacturing Cost |
| ME | Manufacturing Engineer |
| NPV | Net Present Value |
| OC | Other Costs |
| OEE | Overall Equipment Effectiveness |
| OEM | Original Equipment Manufacturer |
| PO | Purchase Order |
| PPD | Production Planning Document |
| RFI | Request for Interest |
| RFQ | Request for Quote |

| | |
|------|---|
| ROI | Return on investment |
| ROM | Rough Order of Magnitude |
| SDE | Supplier Design Engineer |
| SIE | Supplier Integration Engineer |
| SoA | Scope of Automation |
| SOW | Statement of Work |
| T100 | The 100 th Ship Set. This is often the ship set that production planners use to estimate assembly times for their PPDs |
| WACC | Weighted Average Cost of Capital |
| WI | Work Instruction |

Chapter 1 – Introduction

In 2012 American Industrial Partners (AIP) formed Ascent Aerospace (Ascent), a conglomerate of aerospace suppliers that is a leading provider of aerospace factory and assembly line integration products. In the past, automation and tooling suppliers were separate entities where the original equipment manufacturer (OEM) would serve as the integrator. Ascent’s value proposition is a “one stop shop” that succinctly delivers both automation and tooling to an OEM onsite through Ascent’s integration team. This thesis adds to this effort by developing a tool that quantifies the value Ascent’s automation product can add to an OEM’s manual assembly line. By way of introduction, the motivation behind the project is explored followed by a broad overview of the thesis content.

1.1 Problem Statement

As the automated aircraft assembly industry evolves, past automation implementation failures are causing OEMs to enforce stricter levels of Overall Equipment Effectiveness (OEE) requirements in the Purchase Order (PO) and Statement of Work (SOW). If the automation performance does not achieve or exceed the OEE requirements, the automation supplier faces legal and liquidated damages—affecting the profitability of their program.

Automation is widely viewed as one of the best approaches to increase aerospace assembly throughput, yet the aerospace community remains divided on the financial benefits. While automation in aerospace assembly dates back to 1937, there is little substantive research quantifying its business case. This is problematic for both OEMs and suppliers. OEMs are limited by their lack of experience in automating assembly processes and consequently are not able to definitively assess how suitable their assembly line is for automation and the tangible benefit or lack thereof that would result. Therefore, an OEM currently has no means to quantify its willingness to pay for a certain level of automation. Suppliers on the other hand, have knowledge and experience with automation but are also not able to quantify the benefits their automation

provides. This lack of quantifiable insight causes all suppliers in the industry to price their product based on cost rather than the willingness to pay of an OEM. If instead the benefit could be quantified, suppliers could extract maximum compensation while at the same time OEMs would feel at ease having deeper understanding of what they were purchasing.

The hypothesis of this project is that there is, in fact, a quantifiable benefit to implementing assembly automation into a current manual assembly process.

1.2 Thesis Objective

This thesis seeks to solve the problem outlined above by developing a tool that accomplishes two tasks: heighten intuition and improve financially-driven decision-making.

While it is common understanding that automation creates labor, quality, and health & safety benefits there is little intuition into the magnitude of their effects. The financial benefits are seen as a black box: a financial investment goes in and hopefully over the life of a project some savings or increased throughput will result. Even with this lack of intuition, millions of dollars are invested into automation every year in the aerospace industry. The model developed in this thesis can educate OEMs and suppliers on the inherent benefits and limitations of aerospace assembly automation, promoting intuition. Moreover, greater visibility into the financial benefits and costs of automation allows suppliers to price their automation product appropriately and for an OEM to decide whether to invest in automation or not.

1.3 Approach and Methodology

Relationships between aerospace OEMs and their suppliers are often plagued by gamesmanship that results in the Nash Equilibrium of attempting to gain value from the other with less in return. Therefore, the first step to accurately quantify the business case of implementing automation into an OEM manual assembly line is to promote knowledge and information sharing between each party. Developing this symbiotic trusting relationship may take time with a few

iterations of limited sharing, yet only once this relationship is established will accurate data truly flow between parties.

Numerous factors affect both the potential savings and costs associated with automation. This thesis examines each factor and derives equations that only require readily available production and industry standard metrics to quantify their effect. Ultimately the savings and costs are integrated into an NPV analysis that can aid an OEM to decide whether to invest or not.

The model is developed in parallel with a case study where an OEM is seeking to automate a current manual assembly line. This involved numerous meetings between the OEM and Ascent to build the trust required for information sharing. The case study provides valuable insights into the dynamics of the OEM/supplier relationship while also providing an opportunity to trial the model against a real life program.

1.4 Thesis Overview

This thesis seeks to solve the problem of lack of intuition and visibility into the financial benefits automation provides to a traditional aerospace assembly line. A model is developed that accounts for all the major potential savings and costs associated with automation. Below is an outline of the thesis by chapter.

Chapter 2 sets the foundation by introducing the industry and the general steps that are required for fuselage assembly. Next the issues of quality, health & safety, and throughput currently facing aerospace assembly are explored. These issues are contrasted with the potential of automation in the form of ‘One-Up’ assembly. Tempering the automation potential with realization challenges gives the reader suitable context for the rest of the thesis.

Chapter 3 represents the heart of the thesis by deriving the quantifiable savings and costs associated with introducing automation to a manual assembly line, namely the assembly of an aluminum fuselage. First, however, the chapter investigates ways to obtain reliable data for the quantitative analysis. It introduces the power of learning curves, understanding manufacturing

cost metrics, and sets analysis boundary conditions using the Scope of Automation (SoA). From here potential savings are quantified such as labor, quality, health & safety, depreciation tax credits, foregoing rate tooling, and reduced manufacturing floor space. Next costs related to automation such as the initial capital investment, operating costs, and costs associated with unforeseen automation downtime are examined. The chapter concludes with outlining the need for an NPV analysis using the quantified savings and costs to assess whether an automation program makes financial sense.

Chapter 4 focuses on strategies and challenges faced to implement the business case model. The chapter starts by outlining the typical bidding lifecycle for an aerospace assembly program and highlights the strategic objective of a supplier to actively engage an OEM as early in the bidding lifecycle as possible. The second half of the chapter shares how to temper the optimistic implicit bias an OEM has towards automation and how best to promote a positive symbiotic relationship between OEM and supplier.

Chapter 5 applies the business case model developed in Chapter 3 to a case study whereby Company X is looking to automate a manual fuselage assembly line. The case study shows that, based on an initial automation investment of \$12M, the 2000 ship set program had a positive NPV of \$27M. The labor hours saved due to automation was the greatest saving while the risk due to unforeseen downtime was quantified as the greatest potential cost to the program. The chapter concludes by assessing the impact discounting and manual assembly learning effects has on cash flows over the life of the program.

Chapter 6, the final chapter, presents conclusions based on research findings and insights revealed through the financial model. The thesis concludes looking to the future by making recommendations for future study to continue the mission of understanding the true benefit automation provides in aerospace assembly.

Chapter 2 – Aluminum Fuselage Assembly

Overview

An aluminum fuselage is held together by thousands [if not hundreds of thousands] of fasteners, mostly rivets. Assembling an aluminum fuselage is a rigorously repetitive manual process of drilling holes and installing fasteners. Though, the repetitive nature of the assembly process lends itself well to automation applications. Manufacturing experience shows introducing automation into a manual assembly line will have tangible benefits in the form of reduced labor hours, higher quality and productivity, and improved health & safety conditions. [1] Additionally, automation introduces implicit benefits such as negating the need for rate tool capital investments while increasing the productivity per square foot of manufacturing floor space. This section first gives a brief overview of the industry before discussing the current challenges facing manual aircraft assembly and concludes by exploring the opportunities for automation in fuselage assembly.

2.1 Industry Background

The aircraft industry continues to push the performance and efficiency envelope, yet the majority of new aircraft today are built in a similar manner to decades ago. Whether aluminum or otherwise, aircraft are assembled together with fasteners, where rivets account for the vast majority. Since the industry's inception over a century ago, aircraft complexity has constrained the industry to follow manual craft production. Unlike the automation embrace and success seen in the automotive industry, the aircraft industry continues to see lower levels of automation success.

Since deregulation in 1978, airline profitability has followed a cyclical and variable nature with an increasingly significant effect on original equipment manufacturers (OEM's). Entering into the 21st century, aircraft OEM's started to see increasing levels of aircraft order volatility. The volatility can be correlated to the theoretical value of an airlines aircraft fleet at any point in

time. The theoretical value of aircraft depends on many variables yet the most critical are: 1) jet fuel prices, 2) passenger yield and aircraft utilization, 3) cost of capital, and 4) maintenance schedule. [2]

The culmination of the above variables result in volatile aircraft planning and order schedules placed to OEMs. The time lag between order and delivery from current order backlogs only amplifies the volatility through a bullwhip effect. Towards the start of the millennium, Boeing and Airbus each had a cumulative backlog of over 1000 airplanes while delivering an average of about 200 – 300 airplanes per year. Since this time the airline industry has experienced two massive tribulations, the 9/11 attacks and the 2008 financial crisis, yet their cumulative backlogs still increased by a factor of five, see Figure 1.

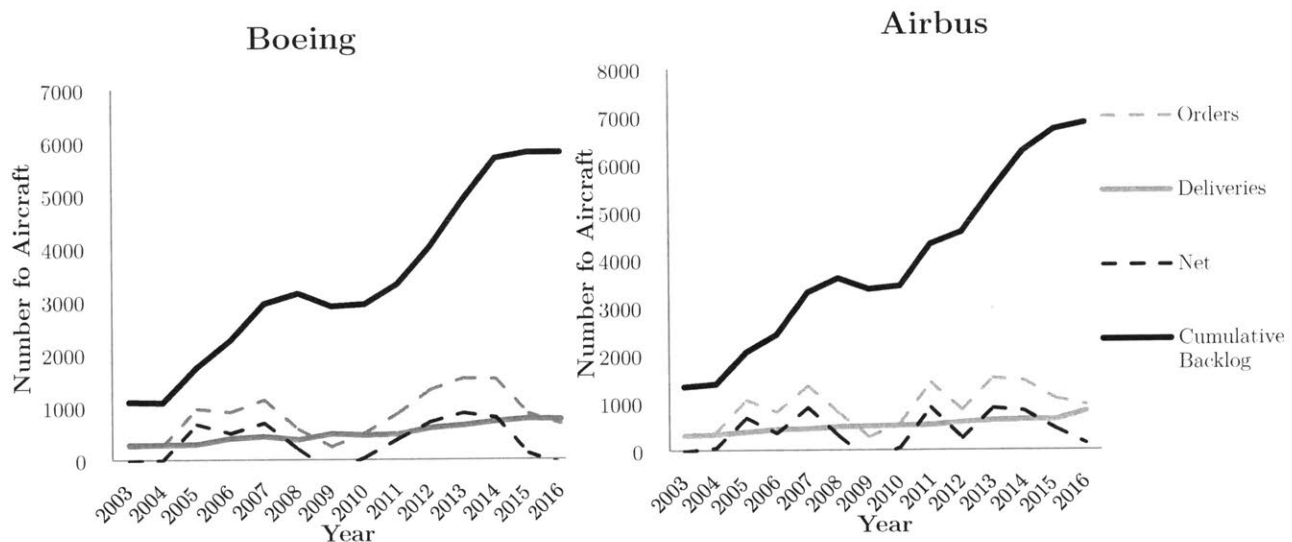


Figure 1: Boeing and Airbus orders and deliveries (2003 - 2016) [3] [4]

Out of necessity, Boeing and Airbus more than doubled their aircraft throughput over the last decade. In 2003 the order backlog of both companies were about 4.5 years yet the current backlogs of Boeing and Airbus stand at six to seven years and nine to ten years respectively. Both companies undertook initiatives to streamline their manufacturing processes with drilling and fastening automation being a major contributor to increased throughput.

2.2 Manual Fuselage Assembly

While every aircraft fuselage is unique, assembling the general structure can be distilled into five general steps.

1. Set-up Assembly Tooling

The first step in the assembly process is staging the aircraft frames and door surrounds into assembly tooling. This forms the substructure of the fuselage. An assembly tool is a large geometrically accurate jig with mounting points to hold the substructure in place. A geometric laser-tracker is used to ensure the substructure is arranged and located within required dimensional tolerances.

2. Temporarily Fasten Fuselage Skin

Once the substructure is secured the aircraft skin and stringer sub assembly is laid overtop, clamped to the substructure, and aligned to assembly datums. Determinant Assembly (DA) holes are used to correctly locate and temporarily fasten the assembly together with either Clicos or 0.098" DIA rivets. To minimize the effect of tolerance stack-ups, DA holes are predrilled or precut by suppliers as part of the Condition of Supply (CoS).

3. Drilling and Countersinking

With the skin secure, a mechanic drills all holes that are common to the skin and substructure. Drill plates are used as hole templates to increase the dimensional accuracy while decreasing the mechanics drilling cycle time. Once all holes for a given drill plate are complete, the mechanic prepares the holes for flush rivets by countersinking the outboard surface of each hole in the fuselage skin.

4. Disassemble and De-burr Holes

Even with the skin securely clamped to the substructure, metal chips and burrs can migrate between the skin and substructure. This is problematic for two reasons: 1) metal chips and burrs between mating surfaces prevents the surfaces from mating cleanly, and 2)

hole burrs can form sharp edges that are susceptible to stress concentrations and possible fatigue crack propagation. Ultimately, metal chips and burrs may prevent a fastener from installing flush with the skin surface. Drilling holes manually as described in (3) above is an uncertain process. It is not possible to approve hole quality through statistical process control (SPC) and therefore every hole must be physically inspected and de-burred by disassembling the entire set-up.

5. Reassemble and Install Permanent Fasteners.

Once hole inspection and de-burring is complete, the set up is reassembled by means of temporary Clico's or permanent tacking fasteners. From here permanent fasteners are installed throughout the assembly. There are thousands of permutations of fastener types in fuselage assembly, however the two main groups are Rivets and Hi-Lites/Hi-Loks, each are briefly described below:

- **Rivets**

Rivets come in a plethora of different shapes, sizes, and material types. In manual fuselage assembly solid aluminum alloy rivets are commonplace and are installed (upset) by the process of bucking. Rivet bucking in fuselage assembly requires two mechanics to stand on either side of the fuselage wall, one on the outside with a pneumatic rivet gun, the other on the inside holding a bucking bar. With a rivet in position, the outboard mechanic excites the rivet head with the pneumatic rivet gun while the other mechanic pushes on the rivet tail with the bucking bar, plastically deforming (upsetting) the rivet.

[5]

- **Hi-Lites/Hi-Loks**

Hi-Lites and Hi-Loks, commonly known as 'shear head' fasteners are a hybrid design between a rivet and typical nut and bolt and only require a single mechanic from one side to install. Shear head fasteners account for over 85 percent of aircraft structural joints. [6] Both are two-piece fasteners: a precision threaded pin, and an internally threaded collar. This fastening system delivers the clamping forces and strength of a bolt that would

otherwise be unachievable with a manually installed rivet while still achieving high-fatigue resistance. The only difference between a Hi-Lite and Hi-Lok is that a Hi-Lite is about 15 percent lighter while still delivering the same clamping and fatigue resistance performance. A Hi-Lite/Hi-Lok is installed in a similar way to a bolt: insert the threaded shaft and torque the internal threaded collar until the “Frangible-driving element” is torqued off. The driving element controls the installation torque of the fastener in a similar way to a torque wrench as shown in Figure 2 below.

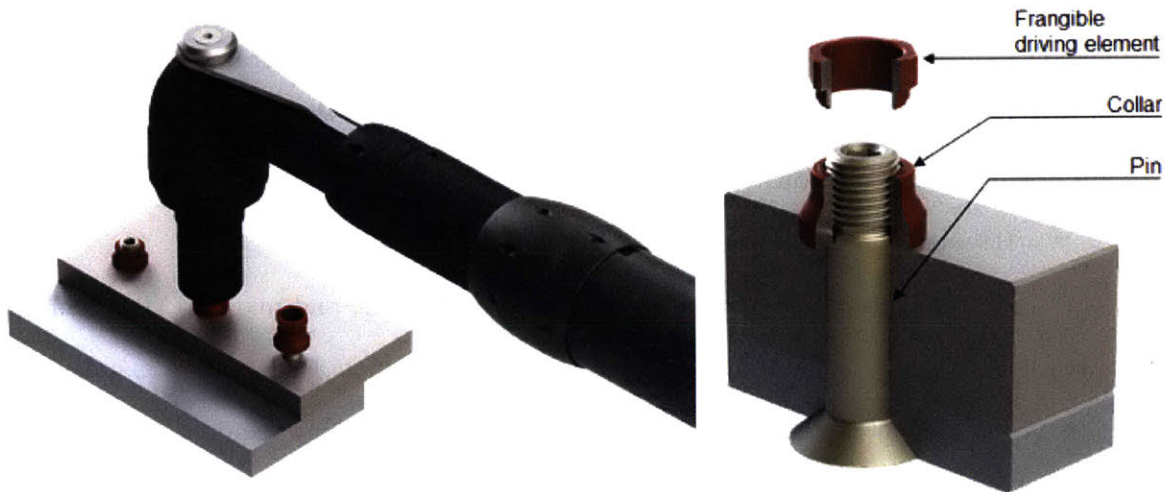


Figure 2: One-sided installation of Hi-Lok/Hi-Lite with power tool [7]

2.3 Issues Facing Manual Fuselage Assembly

Assembly hours are the largest cost contributor during airframe production, consisting of 65% of the overall cost, while sub-assembly fabrication makes up the remaining 35%. [8] The breakdown of airframe assembly cost contributors is given in Figure 3 and reveals drilling and countersinking as the largest contributor to airframe assembly cost.

Airframe Assembly Cost Contributors

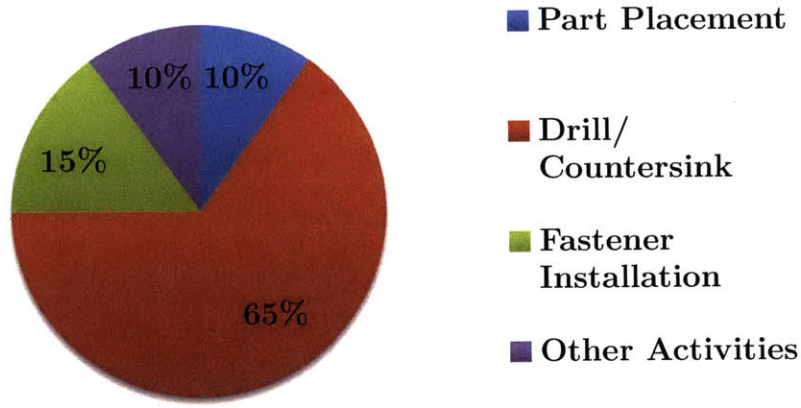


Figure 3: Airframe assembly cost contributors [8]

Moreover, 80 percent of the indirect costs of quality issues and lost labor hours as a result of injury can be attributed just to airframe assembly. [8] Quality and Health & Safety issues are discussed below.

2.3.1 Quality Issues

Assembling an aircraft manually, particularly drilling, countersinking, and installing fasteners is a labor-intensive process. With the number of holes drilled and fasteners installed in the tens of thousands, human error is bound to occur resulting in rework, scrap, or both.

2.3.1.1 Rework

Rework involves the labor required to re-perform the assembly tasks that are not at an acceptable quality standard. Typical rework involves removing the unacceptable fastener, re-drilling the hole to the next standard fastener size up, de-burring the hole, and re-installing a new fastener. The amount of disruption and labor involved in rework is significant and continually drives the industry to the mantra of 'first time quality'.

2.3.1.2 Scrap

Scrap is the material that, due to human error, is not repairable or re-useable and must be discarded. Aerospace grade material and alloys are some of the most costly of any industry due to the overhead of regulation and quality control. Hence, material scrap due to human error can be costly, especially if the part is an entire skin panel for example. While any one defect may be reworked and not be cause for scrap, a collection of subpar quality instances may deem an entire assembly be scraped since the labor cost to repair may out-weigh the cost of new material. As such, the risk and cost associated with scrap increases as the assembly progresses to completion.

2.3.2 Health & Safety Issues

A number of tasks performed during aircraft assembly are intensely repetitive and contribute to Cumulative Trauma Disorders (CTD), also known as repetitive strain injuries. Drilling and installing fasteners are amongst the most repetitive tasks, with bucking rivets arguably the most common CTD-inducing activity in aerospace assembly. In recent years advancements in reduced vibration pneumatic rivet guns have added some comfort to the user, delaying the onset of CTDs. [5] The task of bucking a rivet is physically demanding, often performed by two mechanics. One mechanic stands on the exterior of the fuselage excites a rivet with a pneumatic rivet gun while the other on the interior plastically deforms the rivet tail with a bucking bar. The wrists and arms of both mechanics are subjected to constant jolting and vibrations. A pair of mechanics can install hundreds of rivets within a single shift. Mechanics are cycled through different assembly tasks to allow their wrists to recover and for intellectual stimulation.

2.3.3 Throughput Issues

Perhaps the greatest driver to introduce automation into a manual assembly line is to increase the productivity and throughput. Manual aerospace assembly, like any other manual process, is subject to a learning curve. Learning curve theory predicts the increase in efficiency of labor force

through learning and hence, a potential increase in throughput per labor hour. Yet, in reality production scheduling is often driven by customer needs rather than an optimal manufacturing strategy for the production line. As a result the production schedule is often front loaded where the labor force is still high on the learning curve causing massive strain on labor resources. This is followed by a gradual ramp down of labor needs resulting in a loss of learning and an inefficient use of resources. Production smoothing is discussed in section 7.2 and has the potential to positively impact resource allocation.

Therefore, quality, health & safety, and throughput issues are distinct in nature but interrelated through learning rates and Occupational Safety and Health Administration (OSHA) standards. There is a constant tension between maximizing standard work to increase throughput and quality while cycling mechanics through different tasks to prolong CTD onset.

2.4 Automated Fuselage Assembly

As aircraft backorders approach ten years, OEMs are continuously seeking new technology and processes to increase productivity while maintaining or decreasing manufacturing costs. Automation in aerospace assembly is seen as a necessity and dates back to the 1930's with the creation of 'One-Up' assembly. This sections gives a brief historical overview of aerospace assembly automation before examining One-Up assembly and the industries inherent challenges.

2.4.1 Historical Overview

Automation in manufacturing systems pertains to more than just robots and dates back to the earliest primitive example in the 1500's where water was used to power rolling mills for coinage strips. [9] The aviation industry was birthed about a century after Francois Isaac de Rivaz invented the first automobile powered by a hydrogen internal combustion engine in 1808. A combination of high tolerances, large part size, low throughput, and strict quality regulations has

prevented the aviation industry from ‘leap-fogging’ the automotive industry. Consequently, the aviation industry severely lags the automation maturity of the automotive industry.

Demand for aircraft and investment in aerospace automation seem to go hand in hand. Aviation saw significant advancement and investment in automation during the surge in aircraft demand of WWII. [10] Yet since that time, demand for aircraft remained relatively mild through the second half of the century before picking up in the 1990s. Over the last two decades, volatile fuel prices and surging passenger numbers stirred aircraft demand resulting in growing OEM backlogs. Now, with major OEM backlogs at between six to ten years, there is a high focus on investing in automation once again.

In decades past, automated machines in aerospace assembly were generally large monument style machines that performed a limited number of different tasks, albeit with short cycle times. The monumental size of the machines allowed for high dimensional accuracy when dealing with large aerospace parts. In terms of material handling, one could think of it as always ‘bringing the part to the automation’. Yet, as global competition grows from low cost suppliers in Asia and Central and South America, cost effective flexible automation rather than legacy monument style automation is becoming more desired—‘bringing the automation to the part’. [11] With just a few edits to the CNC code an OEM can use flexible automation for numerous operations and product lines. This allows the OEM to pool automation resources resulting in higher equipment utilization and a lower upfront capital investment.

2.4.2 One-Up Assembly

Since its inception, One-Up has remained the gold standard for automated aerospace assembly. Thomas Speller Sr., founder of Gemcor, first developed the automated One-Up assembly process in 1937. [10] The One-Up assembly process is similar process to that described in section 2.2, yet it uses statistical process control (SPC) to allow fastener installation without the need to disassemble, de-burr the holes, and re-assemble before installing fasteners. Thus, a product is assembled once, drilled, hole quality inspected (if required), sealant applied, and fastener installed.

This eliminates a significant portion of non-value added effort and can substantially reduce the fastening cycle time. Figure 4 presents an overview of the One-Up assembly process.

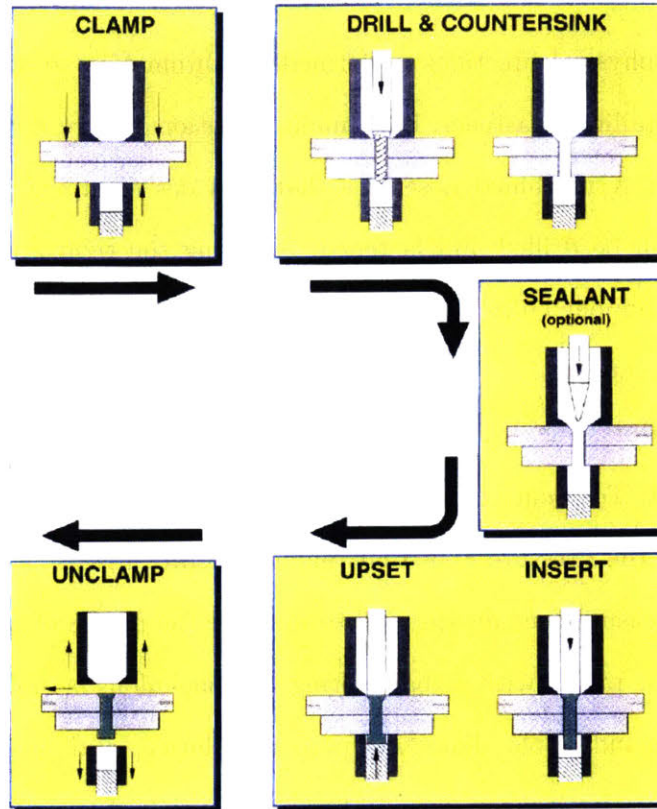


Figure 4: Conventional Automated Fuselage Skin Panel One-Up Assembly

While the One-Up assembly process may appear simple, executing the process with acceptable quality requires the assembly automation to successfully navigate and account for numerous variables. Typical actuation and feedback features allow automation to perform the assembly process with acceptable speed and quality. Actuation and feedback features of aerospace automation are expanded upon in the next section.

2.4.3 Features of Automated Aerospace Assembly

Automation requires two general principles: actuation and feedback. Actuation involves equipment that physically performs the work, while feedback provides sensory signals back to a controller to

navigate the physical environment and adjust for any errors in the system. Features of actuation and feedback that pertain to aerospace assembly are discussed in the following paragraphs.

2.4.3.1 Actuation

Actuation involves the physical functions performed by automation to accomplish a task, in this instance drilling and installing a fastener. Each main actuation feature is outlined below:

- **Pressure Foot:** A machined nosepiece that provides clamping pressure to the stack of material that will be drilled and fastened. Applying the right amount of pressure to not allow any inter-laminar chips or burrs to form while not plastically deforming the surface is critical for hole quality.
- **Drill Spindle:** Holds the drill piece and provides the torque required to drill the holes.
- **Vacuum Assist:** To ensure minimal disruption during the drilling process, a vacuum port is machined into the Pressure Foot that removes metal chips as they form.
- **Hole Probe:** Measurement device used to measure the profile of a drilled hole. A common design involves a probe with a ball spring running along a hole's drilled surface. The measurements include hole diameter, perpendicularity, and inter-laminar burrs. Using SPC, this device is typically removed after a few hundred thousand holes are drilled and the drilling process is within control. Removing the need for a hole probe will significantly reduce the overall automation cycle time.
- **Fastener Insertion:** A fastener is fed, typically through a blow tube, from a fastener feeder system up to the machine head for installation.
- **Fastener Feeder System:** An automated system that delivers fasteners to the machine head. There are many different feeder designs. The two most common are Vibratory Bowls and the F2C2 cartridge system, which are able to deliver a fastener to the machine head every three to four seconds.

- **Sealant Applicator:** Sealant can either be applied to the countersink surface of a hole or the shank and/or countersink surface of a fastener. Both processes require an even film between the mating surfaces once the fastener is installed.
- **Rivet Upset:** There are two common ways to install a rivet. The first is squeezing the rivet from both sides. This requires a machine that can sustain large squeezing pressures. Gemcor have a patented roller screw technology that allows massive squeezing pressures in a compact fashion relative to the common alternative of a ball-screw. The second is when a machine cannot reach both sides of an assembly a pneumatic hammer and bucking bar must be used. While still effective, this process involves a longer upset time with quality results characteristically subpar to squeezing.
- **Motion platform:** The platform that allows the machine head to access an area and install a fastener. Common motion platforms include robotic, guided rail, gantry, and arc frame.

2.4.3.2 Feedback

Feedback sensors help increase the quality of the fastener installation and are described below:

- **Vision:** Substantial advancements in vision systems have dramatically increased the accuracy of vision metrology. Vision feedback is either a passive or active sensor. A passive vision sensor is simply a camera used by an operator to monitor each hole during the drilling process. An active vision sensor is used in metrology to pinpoint a hole location. This eliminates tolerance stack-ups over large assemblies. An active camera can also be used in conjunction with laser scribes to detect the distance and perpendicularity to the surface.
- **Pressure Foot:** Over and above clamping, a pressure foot can also be used to find and assess machine head perpendicularity to the assembly surface.

2.4.4 Realization Challenges

There are challenges implementing automation effectively. Aerospace assembly is generally less suited for automation than automotive for three main reasons: 1) low production rates, 2) part/assembly size, and 3) tight tolerances. The takt time of an airplane can range from a day to weeks yet the takt time of an automobile can be less than a minute. Consequently the initial automation investment in aerospace is amortized over fewer products during its useful life. Furthermore, aerospace parts and assemblies are usually much larger than automotive. Compounding this with the requirements to hold tighter tolerances and the margin of error is greatly reduced relative to the automotive industry. The result is higher scrap and rework rates or a greater investment in more accurate automation. One of the greatest challenges in automated fuselage assembly is during the fuselage ‘tube’ assembly where a single machine cannot reach both side to install fasteners. One method is to use two apposing robots, one drilling and inserting fasteners from the outboard surface, the other upsetting rivets from the inner surface. This is incredibly challenging for the inner robot as it must not only coordinate with the outboard robot but must also navigate the complex landscape of a fuselage’s inner surface. A common compromise to this issue is to continue to use a mechanic on the inner surface to buck rivets or apply swage collars manually. The mechanic uses a remote pendant to coordinate with the outboard robot.

The aforementioned challenges reduce the financial appeal of an aerospace assembly automation investment. An OEM’s return on investment (ROI) is at best pushed out to years in the future or is simply not returned. Nevertheless, as we will discuss in the coming sections, aerospace assembly automation can yield a positive ROI, although, many interdependent variables are involved in developing a robust ROI calculation for automation.

Finally, similarly to other manufacturing systems, aerospace automation faces the challenge of maintaining a high level of Overall Equipment Effectiveness (OEE). OEE is a key performance indicator, set as a percentage, that measures the overall productivity of a system relative to its maximum theoretical productivity. [12] It takes the cumulative effect of three factors into consideration, availability, speed, and quality and is summarized below:

$$OEE = Availability * Speed * Quality$$

Where:

- **Availability** is the percentage ratio of the Uptime to the total available operating time (Uptime and Downtime).

$$Availability = \frac{Uptime}{Total\ Operating\ Time} = \frac{Uptime}{Uptime + Downtime}$$

- **Speed** is a percentage ratio of a systems efficiency or throughput rate relative to its theoretical maximum throughput rate.

$$Speed = \frac{Throughput}{Maximum\ Throughput} = \frac{Minimum\ Takt\ Time}{Takt\ Time}$$

- **Quality** is the percentage yield of units within specification.

Therefore to maximize OEE the manufacturing process should seek to maximize machine uptime (availability), minimize takt time (speed), and minimize defects (quality).

2.4.5 The Future – Flexible Automation

Flexible automation allows customers to pool their automation by either performing more than one operation on the same aircraft or by performing the same operation on many different aircraft. Articulating robotic arms are common flexible motion platforms that can be adapted to a new process or task by just reprogramming the CNC code. Modularity design is another classical means to introduce flexibility into automation. Even an inflexible motion platform with interchangeable end effectors or an end effector with interchangeable actuation units allows customers to pool their automation resources, resulting in a lower overall capital investment.

Ultimately, flexibility increases a machine's utilization, which in turn will decrease the timeframe for the associated ROI.

2.5 Summary

Mounting aircraft order backlogs are placing more pressure on OEM aerospace assembly lines than ever before to increase throughput. Labor, quality, health & safety, and throughput issues continue to plague the legacy craft practice of manual fuselage assembly since its inception over a century ago. It is clear that new innovative manufacturing practices are required for OEM's production lines to keep up. As such, the industry sees the necessity of introducing automation as part of fuselage drilling and fastener installation. Yet, automation is only part of the solution as the physical and technological constraints limit its applicability to certain operations. As automation technology in aerospace continues to evolve and proliferate, particularly toward flexible automation, the inherent benefits will set OEMs on the path towards achieving their productivity targets. The next chapter attempts to quantify the benefits and costs of implementing automation into an aerospace assembly line.

Chapter 3 – Quantifying the Business Case for Automation in Aerospace Assembly

Automation is widely viewed as one of the best approaches to increase aerospace assembly throughput, yet the aerospace community remains divided on the financial benefits. While automation in aerospace assembly dates back to 1937, there is little substantive research quantifying its business case.

As with any business case investigation, the accuracy depends heavily on the underlying data and assumptions. This investigation takes a systems approach to investigate not only the benefits of automation benchmarked against a manual assembly line but also how the true benefits of automation vary throughout a project. It is imperative to establish the appropriate context for the investigation by benchmarking it against a purely manual assembly process. Only then can a true cost/benefit analysis of automation be quantified.

3.1 Capturing Reliable Data

This section describes how to obtain reliable data for quantitative analysis. One of the first and greatest challenges of an automation project is creating a conduit whereby information is shared freely between OEM and supplier. This is particularly challenging during contract negotiations where information sharing is critical to eliminate ambiguous expectations written into the Purchase Order (PO). Early in a manual assembly build program, the OEM's production data is often inconsistent or misleading since the assembly line is still high up the learning curve. Moreover, if an OEM is using a unique process or one that is proprietary, it may initially limit the flow of reliable data. While both of the scenarios just described are admissible, the outcome is suboptimal, requiring much rework and churn during the design and build phase and ultimately a product that potentially falls short of the OEM's expectations. Appendix B lists the minimal preliminary inputs required from an OEM to calculate the ROI for an automation project. Much

of the data outlined in Appendix B are standard manufacturing metrics that should be readily available to an OEM. There are however, a few variables the supplier is responsible for such as Scope of Automation (SoA) and labor savings due to automation as these are the metrics that will directly effect what the supplier is accountable for in the signed contract. This discussion begins with a background on learning curves as an intuitive understanding of production learning is required throughout the investigation. Next, critical manufacturing cost metrics and assumptions are established before deriving an important analysis boundary condition: the Scope of Automation.

3.1.1 Production Learning Curves

Arguably the most fundamental driving force behind any production planning analysis is the manual assembly learning curve. Theodore Paul Wright first quantified learning theory in 1936 in relation to aircraft production with further studies during the aircraft production of WWII. [13] Learning curve theory suggests a relatively consistent amount of learning occurs every time the cumulative number of units produced doubles. [14] Two widely used models are: the “Unit” (U) model from Crawford and the “Cumulative average” (CA) model from Wright. [15] Both models have similar mathematical assumptions, one is not more accurate than the other, yet are distinct in their results. The U model predicts that every time the cumulative number of units produced doubles there is a consistent percentage decrease in the effort to produce a new unit. A similar prediction is made for the CA model yet it is in terms of the average time required to build a group of units. [15] For mathematical simplicity this investigation will use the U model, as tracking the number of labor hours per ship set is a more intuitive and translatable data set for the “Efficiency Factor”—introduced later in this chapter.

The U model learning curve is based off the common power law and is defined as:

$$\mathbf{H}_n = H_1 n^b \tag{3-1}$$

Here n is the n^{th} unit of production, H_n is the hours required for the n^{th} unit of production, H_1 is the hours required for the first unit of production, and b is the “natural slope” of the learning curve. The natural slope of a U model is expressed as either a negative or positive decimal corresponding to whether learning or forgetting is occurring. Interpreting b is not intuitive as it is the slope of a log-log plot; therefore, experts developed an industry wide standard to express the learning rate as a percentage. A 100% learning rate resembles zero learning while 0% implies an infinite amount of learning, if such a thing were possible. A learning rate that is greater than 100% corresponds to negative learning (forgetting). Forgetting could be attributed to interruptions in production or a high employment turn over on the production line. [15]

Given the assumption that every time the cumulative production quantity doubles a set amount of learning b occurs, we can derive a relationship for b in terms of a learning rate (ξ). First, using the U model we find a relationship between the n^{th} and $2n^{\text{th}}$ unit of production in terms of the natural slope b :

$$H_{2n} = H_1(2n)^b \tag{3-2}$$

Dividing (3-2) by (3-1)

$$\frac{H_{2n}}{H_n} = \frac{2n^b}{n^b} = (2)^b \tag{3-3}$$

Second, the industry standard expressing the learning rate between the n^{th} and $2n^{\text{th}}$ unit of production is as follows:

$$\frac{H_{2n}}{H_n} = \xi \tag{3-4}$$

ξ : Learning Rate (%)

Finally, setting Equations (3-3) and (3-4) equal to each other and rearranging for b :

$$(2)^b = \xi$$

$$b * \log(2) = \log(\xi)$$

$$b = \frac{\log(\xi)}{\log(2)} = \log_2(\xi) \quad (3-5)$$

Airframe assembly typical experiences learning curves in the order of 85 to 87 percent. [15] Therefore, in the U model every time the cumulative number of units produced doubles, the time required to produce unit 2n requires only 85 to 87 percent of the labor hours required by unit n. [15] Substituting the aerospace assembly industry standard learning rate of 85 percent we can calculate the value of b:

$$b = \log_2(85\%) = -0.234$$

Determining the labor hours required for the first unit of production (H_1) is no trivial task. Massive uncertainty surrounds the level of production issues the first few production units will face. To minimize this uncertainty, production planners use data from time studies to develop a planned production hour budget set for unit 100 (H_{100}), often called “T100”. The rationale assumes by unit 100 the production line will be moderately stable and far enough down the learning curve to develop a good first approximation of labor resources required. From a T100 estimate, production planners back calculate using an industry standard learning rate (ξ) to arrive back at H_1 . This mitigates planning error in two ways:

1. Incorporating time study data from previous projects gives insight into estimating the hours required.
2. While H_{100} is unlikely to be correct from this first approximation, as production continues down the learning curve toward H_{100} new production information becomes available that

can be used to reassess the learning curve parameters, make corrections and reduce the overall error.

With the critical characteristics of unit production learning curves defined, our investigation introduces a variable that tends to be overlooked during Business Case calculations: the Efficiency Factor.

3.1.2 The Efficiency Factor

To understand the true benefits of automation to a manual assembly line the learning effects discussed in section 3.1.1 need to be captured and accounted for in our investigation. Introducing the Efficiency Factor (EF_n) for a given ship set n that calculates the relative efficiency of the n^{th} ship set to the productivity base point of T100 (H_{100}). EF_n is a non-negative multiplication factor that can be greater or less than unity depending if the efficiency of the n^{th} ship set is less or greater than that of the 100th unit respectfully, see Table 1. Note EF_{100} is equal to unity. EF_n is used to ensure learning effects are assigned correctly to the potential labor savings due to automation (discussed in section 3.2.1.3). See Equations (3-6) through (3-8) for the EF_n derivation.

Table 1: Efficiency Factor with respect to the n^{th} unit of production

| n^{th} unit | $n < 100$ | $n = 100$ | $n > 100$ |
|----------------------|-----------|-----------|-----------|
| EF_n | >1 | 1 | <1 |

$$EF_n = \frac{H_n}{H_{100}} \tag{3-6}$$

EF_n : Efficiency Factor at ship set n

H_n : total manual labor hours to assemble ship set n

H_{100} : total manual labor hours at T100 (ship set 100)

Note:

$$H_{100} = H_1 100^b \quad (3-7)$$

Substituting Equations (3-1) and (3-7) into (3-6):

$$EF_n = \frac{H_1 n^b}{H_1 100^b} = \left(\frac{n}{100}\right)^b \quad (3-8)$$

Note that H_n and EF_n have the same power relationship with respect to n and b . EF_n will be incorporated into labor saving calculations later in this chapter. Our next step in capturing reliable data is establishing an OEM's standard manufacturing costs.

3.1.3 Establishing an OEM's Manufacturing Costs

This section briefly describes how to estimate an OEM's fuselage manufacturing costs using labor hours as a proxy. OEM manufacturing costs are used in later chapters to estimate savings and costs due to automation. Please refer to Appendix D for a detailed description with equations. This investigation we will only focus on OEM product costs (direct and indirect) related to manufacturing.

3.1.3.1 Direct Costs

Direct costs (DCs) are costs that are directly related to manufacturing the product such as direct labor, raw material, and other engineering related activities. DCs associated with fuselage manufacture are typically allocated as follows:

- Labor Costs (LC): 70%
- Material Costs (MC): 20%
- Other Costs (OC) [quality assurance, recurring engineering and tooling]: 10% [16]

Above are good first estimates, although the specific allocations to an OEM's direct manufacturing costs may differ. At the outset of an automation program there is little or no

visibility into an OEM's manufacturing costs other than their production learning curve metrics. The above cost allocation assumption allows us to estimate the total manufacturing costs using labor hours as a proxy. From the learning curve model, we can estimate the average labor costs over the entire program and divide it by the LC allocation (70%) to arrive at the average total direct manufacturing cost (\overline{TDMC}).

With \overline{TDMC} , we can use the MC and OC allocations to calculate the average Material (\overline{MC}) and Other (\overline{OC}) costs. Additionally, because we assume that MC and OC remain constant over the life of the program, we can calculate the total direct manufacturing cost for any ship set ($TDMC_n$) by summing the LC for any ship set (LC_n) together with \overline{MC} and \overline{OC} , see Equation (3-9).

$$TDMC_n = LC_n + \overline{MC} + \overline{OC} \quad (3-9)$$

3.1.3.2 Indirect Costs

Indirect costs are costs that cannot be attributed to making one particular product but are absorbed across many production lines and products. Resources that are pooled together under Overhead (OH) such as utilities, equipment, management labor, and tooling are common indirect manufacturing costs and from Ascent's experience 20% of DCs is a good first approximation.

While there are many ways to allocate OH, this investigation simply adds 20% of the \overline{TDMC} to each ship set to arrive at the total manufacturing cost for each ship set (TMC_n), see Equation (3-10).

$$TMC_n = TDMC_n + OH \quad (3-10)$$

The Scope of Automation is the next factor to discuss in the pursuit of capturing reliable data as it sets the automation boundaries for our investigation.

3.1.4 Scope of Automation

The Scope of Automation (SoA) is the proportion of assembly hours that will now coordinate with automation. Determining the SoA is no trivial task but one that requires contribution from many stakeholders. At the outset of an automation project, the following data inputs are required:

- **OEM Production Planning Documents (PPD):** Documents that detail the OEM's current manual assembly process including part/assembly numbers and predicts the associated labor hours for each production step for a specific ship set, typically the 100th unit (T100). It is highly recommended to have a digital version of the PPDs in Excel or an equivalent means to filter assembly tasks as required.
- **Aircraft Computer Aided Design (CAD) Assembly Data:** Aircraft CAD assembly data is used to assess each fastener's accessibility and whether it can be installed with automation.
- **Access to the OEM's production floor:** Walking through the production line while witnessing the assembly process will add significant context to the PPDs.

A significant number of stakeholders make up any automation project team. Excluding management, the critical stakeholders who will have a meaningful impact on the success of a project are:

- **Supplier Design Engineers (SDE):** Both tooling and automation design engineers work closely together to ensure that tooling and automation integrate and function effectively.
- **Supplier Integration Engineers (SIE):** SIEs are responsible to automate the assembly line by coupling tooling and automation. Together with the SDEs they identify areas in the manual assembly line that are suitable for automation and determine the consequent effect on the assembly line as a whole.
- **OEM Manufacturing Mechanics (Mechanics):** Mechanics can provide valuable insights into the assembly process and highlight areas where automation is best suited.
- **OEM Manufacturing Engineers (ME):** MEs help expedite the learning process of understanding the current PPDs.

Arriving at an automation solution tends to follow an iterative process of re-assessing the SoA as each stakeholder becomes more familiar with the PPDs. To expedite PPD familiarity, each manual assembly step within a tooling station is scrutinized to understand how suitable it is for automation. SDEs and SIEs go to Gemba, assessing the PPDs and CAD data while on the manufacturing floor, observing the manual assembly process in action. Here, SDEs and SIEs not only gain an appreciation for the manual operations that will be replicated with automation but also form the foundations of a collaborative relationship with the Mechanics and MEs. Establishing a collaborative relationship with an OEM's staff is critical as they are a wealth of knowledge on the current assembly process and will be vital advocates for automation.

Once the assembly process is understood, the SDEs and SIEs identify applicable areas for automation. Naturally, any fastening tasks that require a high proportion of repetitive fastening with reasonable accessibility, such as fuselage skin fastening, are ideal candidates for automation. Common assembly categories (AX) include:

- Longitudinal aircraft fuselage skin splice joints
- Circumferential aircraft fuselage skin splice joints
- Door Surround to aircraft fuselage skin fastening
- Shear tie to fuselage skin fastening
- Shear tie to aircraft airframe fastening

Each production step in the PPDs that relate to any of the above candidates is further analyzed to quantify the ratio of automated fasteners to those remaining as manually tacked fasteners. From here, using the PPDs as a baseline, the total labor savings for each production area are calculated leading to the effect on the assembly line as a whole. The first step in this process is evaluating fastener automation applicability.

3.1.4.1 Fastener Automation Applicability

Every fastener within the SoA is assessed based on its type, accessibility, and whether it is a suitable DA fastener that will remain manually tacked. However, the greatest challenge for an automation designer is the spatial constraints around fastener accessibility.

Investigating fastener accessibility through a ‘Reach Study’ is critical to maximizing the value of automation. Together with the aircraft CAD data, a SDE develops a geometrically simplified yet conservative version of a current end effector design and assesses the accessibility of each fastener. Pending its accessibility, the fastener is designated a color and placed into one of four categories that describe the significance of the end effector design modification. Figure 5 below describes the four categories and demonstrates a fictitious situation where rivet accessibility is assessed for an aircraft shear-tie to aircraft frame assembly category.

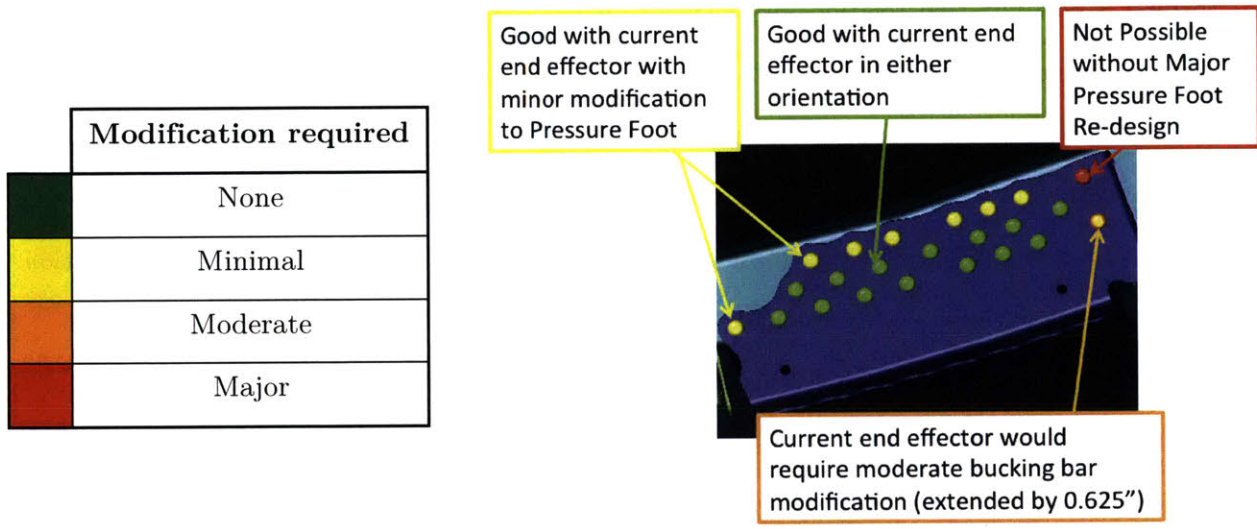


Figure 5: Fastener automation accessibility study

Once the accessibility of each fastener is categorized, the SDEs and SIEs evaluate whether a given fastener is suitable as a DA manually tacked fastener. This step requires close communication with the Mechanics and MEs as any design change will require an Engineering Change Notice (ECN) sent to an OEM’s supplier.

3.1.4.2 Calculating Percent of Automated Fasteners

SDEs evaluate the findings of the Reach Study and quantify the modification costs to the current end effector design to incorporate a group of fasteners that are inaccessible. If the costs outweigh the benefit of a certain category of fasteners, the fasteners are added to the manually tacked fasteners category and recolor-coded accordingly.

Finally, after each fastener is allocated a color, the percentage of automated fasteners versus manually tacked fasteners for each assembly category (AX) can be determined from Equations (3-11) and (3-12):

$$\alpha_{AX} = \gamma_{AX} - \beta_{AX} \quad (3-11)$$

α_{AX} : Number of automated fasteners within an AX

β_{AX} : Number of manually tacked fasteners within an AX

γ_{AX} : Total number of fasteners within an AX

Hence,

$$\kappa_{AX} = \frac{\alpha_{AX}}{\gamma_{AX}} \quad (3-12)$$

κ_{AX} : Percent of automated fasteners within an AX

κ_{AX} is critical to calculating the labor hours saved due to automation—discussed later in this chapter. The next step is to establish typical assembly cycle times for manual and automated processes.

3.1.4.3 Establishing Standard Manual and Automated Assembly Cycle Times

The final step in capturing reliable data is establishing the standard manual and automated assembly cycle times. The standard manual assembly process outlined in the PPDs is typically set for SS₁₀₀. The PPDs take into account historical time studies and production learning curve data to predict the manual assembly task cycle times for a given ship set. Since this investigation is only focusing on assembly steps that will be automated, the total manual assembly time (TMAT) is limited to within the SoA. Furthermore, for all discussion moving forward we will only consider assembly hours within the SoA for each ship set n (SoA _{n}). Appendix E describes the process to

establish the standard manual and automated assembly cycle times in detail. Recalling section 2.2, the general labor steps associated to manually install fasteners are:

1. Set up assembly tooling
2. Temporarily fasten fuselage skin
3. Drilling and countersinking
4. Disassemble & de-burr holes
5. Reassemble and install fasteners

Disassembling, de-burring, and re-assembling is non-value added work which is eliminated by the automated One-Up assembly process. As described in section 2.4.2, One-Up assembly assembles once, drills and installs fasteners with first pass quality resulting in substantial cycle time savings. Once standard manual and automation cycle times are set they are combined with κ_{AX} to find the labor savings by taking the difference between a fully manual and automated assembly process, see section 3.2.1.1.

3.2 Quantifying the True Benefit of an Automation Program

Quantifying the benefits automation will have on a manual assembly line requires a perspective that is benchmarked against the parallel scenario of a purely manual assembly process. Benefits from an automation program can be placed into six general categories:

- **Labor:** The direct labor savings for each ship set due to a reduced cycle time using automation relative to a manual assembly process.
- **Quality:** The two fold benefit of labor savings from reduced rework and material cost savings from reduced material scrap.
- **Health & Safety:** Fewer Cumulative Trauma Disorders (CTDs) resulting in fewer lost labor hours and medical expenses.

- **Depreciation Tax Shield:** Tax rules allow depreciation of automation equipment for tax purposes.
- **Avoidable Rate Tooling:** The inherent opportunity savings relative to further tooling investments required by a manual assembly line during ramp up.
- **Manufacturing Floor Area:** Floor space savings.

3.2.1 Labor Savings

This section summarizes a standard process of quantifying the labor savings due to automation. For an in depth description of the equations involved please refer to Appendix F. Furthermore, this section divulges further potential opportunities for labor savings over and above automation and develops a prediction model that uses supplier historical data to predict the labor savings with only the data available from an OEM's Request for Interest (RFI).

3.2.1.1 Calculating Labor Hour Savings

With automation installed, the new automated assembly process consists of two parts: 1) manual tacking and 2) automation assembly time. Manual tacking time (TT) is estimated as the equivalent proportion of TMAT associated with manually tacked fasteners. Whereas the automation labor time (AT) is simply the number of automated fasteners multiplied by the standard automation cycle time (ACT) established in section 3.1.4.3. Hence, the total automated assembly time (TAAT) for the new automated process is the sum of TT and AT. While the total labor hour savings (TLHS) is the difference between the TMAT and TAAT.

What was just described is the process to calculate $TLHS_{100}$. This represents the maximum potential hour savings available for this assembly line (according to the PPDs) at ship set 100 (SS_{100}). However two factors work to vary its potential effect in practice with each ship set:

1. **Automation integration period:** The period where the OEM's technicians are debugging and learning to use the automation

2. **Manual assembly learning effects:** The efficiency improvement of the manual line due to learning if automation was not introduced to the line.

Each factor is discussed below.

3.2.1.2 Automation Integration Period

Unlike a manual assembly process, implementing automation does not have a continuous learning curve. There is certainly a period of learning for the technician, yet once a technician is trained and debugging is complete the full potential of the automation benefit is realized. The integration period varies somewhat between projects and technicians. However, in Ascent's experience debugging and technician learning typically requires 10 to 20 ship sets after the implementation ship set (ISS) before the full benefit of automation is realized. The integration period is a user defined input and can be whatever an OEM is comfortable with but for the purpose of this model we will assume a linear integration period over 20 ship sets. The mathematical representation of this is given in Appendix F.

3.2.1.3 Manual Assembly Learning Effects

As previously mentioned in section 3.1.4, the potential labor hour savings are set according to the PPDs at a specific ship set, typically SS_{100} . Yet, as the alternate scenario of an assembly process without automation continues down its learning curve from SS_{100} , $TLHS_n$ will not remain constant but decrease proportionally to the learning curve. On the other hand, if we back calculate up the learning curve to ISS, $TLHS_n$ will instead increase proportionally to the learning curve. The manual assembly learning effects are accounted for by re-introducing the Efficiency Factor of Ship Set n (EF_n). Thus, the Actual Labor Hours Saved ($ALHS_n$) is found through Equation (3-13) as the product of $TLHS_n$ and EF_n .

$$ALHS_n = TLHS_n * EF_n \quad (3-13)$$

ALHS_n: Actual labor hours saved due to automation for ship set n. This quantity accounts for the learning effects happening in the alternate scenario of an assembly process without automation

3.2.1.4 Calculating Labor Dollar Savings

Finally, the labor dollar savings for year y are calculated by multiplying the total ALHS for year y by the OEM's blended labor rate (LR). The general equation is given in Equation (3-14):

$$LS_y = \sum_{n \in y} ALHS_n * LR \quad (3-14)$$

LS_y: Monetary labor savings for all ship sets within a given year y

3.2.1.5 Further Opportunities for Labor Savings

Introducing automation into a manual assembly line allows for labor saving opportunities beyond just the difference in fastener installation cycle times. A few opportunities include: improved Material Handling, increasing the Condition of Supply (CoS), and tacking with Cleco's instead of permanent fasteners.

Material Handling redesign, now with automation in mind, reveals significant benefit, both in labor hour savings and quality improvements when a production system is designed for minimal tool changes. Installing casters or air bearings at the base of assembly tooling is an effective technique to reduce tool changes, as it eliminates labor-intensive part de-tooling. Instead of removing an assembly from a tool within an automation station, an entire assembly tool is swapped out with the next tool within minutes. This will significantly reduce non-value added tooling changes, increasing the utilization of the automation station. Moreover, since the assembly remains undisturbed in the tooling station, assembly tolerance stack-ups are minimized, increasing the assembly quality of the build.

One critical aspect of any assembly production line is the 'make vs. buy' tradeoff, known as the "Condition of Supply" (CoS). Simply, it is evaluating the cost/benefit of performing more or less of the assembly work in house relative to suppliers. The CoS dictates the level of assembly

or fabrication (condition) suppliers provide to the OEM. If an OEM has high labor rates and is looking to reduce labor hours it may be cost effective to increase the CoS and push assembly work upstream onto a supplier. This however, is only effective for the production system as a whole if the suppliers have 1) lower labor rates, 2) capacity to accept the increase in scope, and 3) robust supply chain and quality management systems that can meet on time deliveries. Keep in mind increasing the CoS increases the material cost to the OEM. Moreover, the OEM will need to approve every change made to the CoS. The approval process could be as simple addition to an ECN or require significant Design for Manufacture and Assembly (DMFA), stress, and fatigue analyses. Therefore care must be taken before making a change to the CoS and requesting an ECN.

Finally, while the number of tacked fasteners is a significantly less than before, the process still requires each hole be inspected and de-burred before permanently installing a fastener. Tacking pre-drilled DA holes with Cleco temporary fasteners instead of permanent fasteners eliminates non-value hole inspection and de-burr steps. Instead, after all non-tacked fasteners are installed, the Clecos are removed and fasteners installed with One-up assembly. It must be noted that Clecos cannot be used in every situation. For example, door surrounds and shear tie fastening require manually tacked fasteners.

3.2.1.6 Estimate Labor Savings from OEM RFI Data

The Author has developed a means to estimate the labor savings due to automation using a combination of a supplier's historical data from past automation programs and a current OEM's RFI. This quantifies the benefit of automation within an hour or so of work instead of weeks in a Reach Study and PPD investigations. While it is a useful tool it is beyond the scope of this thesis. If this is of interest to the reader a detailed description is included in Appendix F.

3.2.2 Quality Savings

Quality issues continue to be one of the greatest ongoing challenges facing the aerospace industry. AS9100D is the latest revision of the AS9100 aerospace quality management system that outlines quality, safety, and delivery compliance standards for the commercial and military industries. The high level of quality required by the aerospace industry results in high rework and scrap rates, in the order of 10% or more, and as high as 16% in the case of Lockheed Martin's F-35. [17] Therefore any savings that arise from increased quality are two fold: 1) less rework labor hours and 2) less material scrap. The mathematical representation is given in Appendix G and described below.

Annual rework savings (ρ_y) per year are found by summing the labor costs for a given year within the SoA and multiplying it by the average rework rate and a "reduction rate" since rework is not fully eliminated. There is also a factor of two applied since rework hours includes time spent both removing and reinstalling a fastener.

Annual scrap savings (σ_y) per year are calculated in a similar manner by summing the material costs for a given year within the SoA and multiplying it by the average scrap rate and a "reduction rate" since scrap is also not fully eliminated.

Finally, the total quality savings (TQS_y) per year y from automation is the sum of rework and scrap savings.

3.2.3 Health & Safety Savings

Much of aerospace assembly, particularly fuselage assembly is heavily repetitive and labor intensive. The repetitive nature of fuselage assembly is ideally suited to automation. Perhaps the most labor-intensive repetitive task involved in aerospace assembly involves bucking rivets. The process causes significant repetitive stresses and vibrations through the wrists and arms of the mechanics.

Obtaining an OEM's injury metrics can be challenging, however, from Ascent's experience typical injury rates in aerospace range from two to eight injuries per million-labor hours with the average cost of an injury totaling to an average of US\$30,000 [8].

To calculate the annual savings from increased health & safety ($H\&SS_y$) for year y we multiply our annual SoA by the injury rate, average cost per injury, and reduction in injury rate since some smaller number of injuries still persist after automation is installed. The mathematical representation is given in Appendix H.

3.2.4 Cash Flow from Depreciation Tax Credit

Automation capital equipment can be depreciated resulting in an income tax deduction against operating costs. To maximize the value of the tax deduction, this investigation accelerates depreciation using the Modified Accelerated Cost Recovery System (MARCS). MARCS requires the following inputs:

- **Asset Class:** It is critical to use the correct Asset Class as this affects the capital equipment's useful life. The Asset Class for aerospace assembly automation is 37.2: Manufacture of Aerospace Products with a corresponding seven-year useful life according to the General Depreciation System (GDS). [18]
- **Convention:** The averaging convention sets when the recovery period begins and ends with the specific convention dictating the number of months you claim depreciation in the inception and disposal years. The convention options include: Mid-month, mid-quarter, and half-year. [18]
- **Depreciation Method:** MARCS has three depreciation methods, two declining balance methods (150% and 200%) and a straight-line method. Both declining balance methods accelerate depreciation and change to straight-line when that method provides greater than or equal deductions. [18]

The annual depreciation tax credit for a given year is calculated by multiplying the annual deduction by the tax rate.

3.2.5 Rate Tool Savings

Purchasing rate tooling is common practice during the lifecycle of a manual aerospace assembly project. However, it is normally not required if the project involves automation since the initial capacity is designed for full rate production. Rate tooling is often purchased further along the production schedule as production ramps up to full rate. The option to purchase rate tooling at a later date has two distinct benefits for an OEM: 1) it smooths capital expenditure by delaying it to later in the program, and 2) allows time for learning, creating a real option for the OEM to make a more accurate rate tooling assessment when more production information is available.

The main assumption in this section is that an automation program does not require extra tooling as production ramps up to full rate. Assessing the level of rate tooling required for a manual assembly line during ramp up depends directly on how the annual production hours will vary relative to the baseline production in year one. Generally speaking, further investments in rate tooling are made when the production schedule demands throughput that cannot be managed by the labor force. The limiting factor of an assembly station is how many mechanics an assembly station can hold while still allowing them to work effectively. Accordingly, rate tooling is purchased to allow more mechanics to work to increase production throughput. Lastly, once rate tooling is purchased it cannot be returned since it is designed and built for a specific aircraft. Therefore, if an OEM chooses not to use automation it is prudent to smooth the production schedule with respect to the production learning curve to minimize rate-tooling investments. See section 7.2 for a brief discussion of production smoothing.

Quantifying the rate tool savings is a fairly involved undertaking. The mathematical representation is given in Appendix I.

3.2.6 Floor Space Savings

Given rate tooling is not required for an automated assembly line, it will require less manufacturing floor space. Consequently, the manufacturing productivity per square foot increases

when automation is installed. Higher floor area productivity leads to floor space savings that are quantified by two mutually exclusive means:

1. The opportunity profit generated by another program using the floor area that would otherwise be occupied by the rate tooling of a manual assembly line.
2. The potential added cost to rent out further manufacturing floor area.

The floor space savings due to automation is probably the most elusive potential savings to calculate. While it is ideal to calculate the floor savings using both techniques and comparing, this is not always achievable and depends on available input data.

3.2.7 Labor Savings and Increased Throughput Dichotomy

As the reader may have noted, the above analysis had no mention of the benefits from a potential increase in throughput from automation. An increase in throughput stems from the reduced cycle time of drilling and/or installing fasteners with automation relative to a manual assembly process. This benefit could be quantified by calculating the increase in annual Earnings Before Interest and Taxes (EBIT) from the greater number of aircraft built each year. However, in the above analysis the benefit of increased throughput is already captured in the labor hour savings derived in section 3.2.1 since there is an underlying assumption that throughput is fixed, pushing all cycle time savings into labor savings.

Quantifying the benefit of either labor hour savings or increased throughput can only take one of two approaches. The approach derived in section 3.2.1 assumed a fixed throughput according to the production schedule. Consequently, if the required throughput stays constant, cycle time savings manifest in the form of labor savings, as less man-hours are now required to perform the same level of output. On the other hand, if throughput were no longer bounded by the production schedule and the assembly station in question was on the critical path (i.e. a bottleneck), then for a given number of man-hours, throughput would increase as a result of automation. The increase in throughput derives from the available resource (labor) remaining constant yet becoming more efficient, resulting in an increase in output (throughput). However,

this would only occur up to the point where the said assembly station is no longer on the critical path. Any increases in efficiency for a station that is no longer the bottleneck will not result in an increase in throughput for the assembly line. It is therefore much more difficult to quantify the increase in throughput of the assembly line since the analysis needs to include and intimate a system wide simulation of the assembly line.

3.3 Quantifying the True Costs of an Automation Program

With the true benefits of implementing automation understood, the costs of automation will be investigated. Understanding the true costs of implementing automation is critical for a realistic and accurate depiction of the implicit benefit automation provides. Without a firm grasp of the actual costs involved, the investigation's results could run unrealistically optimistic. Costs involved in an automation program can be placed into three general categories:

- **Initial Automation Capital Expenditure:** Initial capital expenditure over and above that required for a manual assembly line
- **Automation Operating Costs:** Operating costs that would otherwise not exist in a manual assembly line
- **Unforeseen Breakdown Risk:** The cost allocated to the risk of unforeseen automation breakdowns holding up production

3.3.1 Initial Automation Capital Expenditure

The most scrutinized cost to an OEM is the initial capital expenditure of an automation program. However, it is imperative to recognize the actual initial capital investment for automation is only what is over and above that required for a manual assembly line. This is due to the fact that an automation program includes a similar level of initial tooling to that of a manual assembly line.

Consequently, the actual initial capital investment is only the difference between the automation and manual tooling programs as demonstrated by Equation (3-15).

$$\begin{aligned}
 & \textit{Initial Automation Capital Expenditure} \\
 & = \textit{Total Investment (Automation Program)} \qquad (3-15) \\
 & - \textit{Total Initial Investment (Manual Assembly Program)}
 \end{aligned}$$

Figure 6 is a general guide into relative initial capital investment costs between an automation and manual assembly program.

| Automation Program | |
|---------------------------------|-----------------------|
| Tooling Investment | \$\$ |
| Automation Investment | \$\$\$ |
| Integration | \$\$ |
| Total Initial Investment | \$\$\$\$\$\$\$ |

| Manual Assembly Program | |
|---------------------------------|-----------------|
| Initial Tooling Investment | \$\$\$ |
| - | - |
| Integration | \$ |
| Total Initial Investment | \$\$\$\$ |

Figure 6: General guide to capital investment of automation vs. manual assembly programs

Substituting Figure 6 into (3-15) we get the following fictitious result:

$$\textit{Initial Automation Capital Expenditure} = \$$$$$\$ - \$$$$ = $$$$$

Figure 6 highlights three categories that make up an initial automation capital investment: tooling, automation, and integration. Each is outlined below:

- Tooling Investment:** An initial tooling investment is usually higher for a manual assembly program. This is driven by the need for drill plates, typically adding an extra 15 to 20 percent of tooling costs. Since automation is integrated onto the same tooling footprint, a fair assumption is that apart from drill plates, the initial tooling investment of each program is the same.

- **Automation Investment:** This investment is specific to an automation program and covers the costs associated to design, build, and deliver the automation required for the program.
- **Integration:** The integration investment covers the costs associated with integrating the automation and tooling into the assembly line. Integration costs related to automation are much higher than those related to tooling. This is driven by CNC programming and debugging over and above the geometric laser-tracking set-up required for tooling.

Note: Recalling section 3.2.5, a manual assembly program will also include “Rate Tooling” which is purchased and implemented as the production line ramps up to full rate. This consideration is not within scope of the initial capital investment and therefore is excluded here. The effect of rate tooling was captured in section 3.2.5 as an opportunity saving for an automation program.

3.3.2 Automation Operating Costs

Automation operating costs (AOC) are incurred to operate and maintain the automation equipment. They are costs incurred specific to automation equipment, which otherwise would not be incurred in a manual assembly line. Based on historical data, for a given machine, a blended AOC burden rate can be calculated and absorbed on a per unit (ship set) basis. Typical costs that factor into the annual AOC burden rate include but not limited to:

- Consumables
- Spare parts
- Maintenance contracts
- Utilities (power, air, oil, cutting fluid etc.)
- Interest expense (over and above that expensed on a manual assembly line)

Note: Other operating costs such as labor, material, and other related overhead are excluded from the AOC burden rate as they are either accounted for in section 3.1.3 or are not

incurred over and above what would already exist in the manual assembly line. The total AOC for a given year is calculated by multiplying the annual production quantity by the AOC burden rate.

3.3.3 Automation Unforeseen Downtime Risk:

An OEM's RFI will specify a maximum allowable annual automation downtime before liquidated damages are incurred. Downtime is often expressed in percentage form of available production hours per year. Given that costs related to the automation repair and maintenance contract are sunk, the cost of risk associated with automation downtime is the lost opportunity revenue as a result of the unexpected downtime. Calculating the annual automation downtime cost for a given year requires three general steps:

1. Calculate actual production hours (APH) by multiplying the available production hours per year by a productivity rate and hence obtain the tolerated number of annual downtime hours.
2. Determine how much revenue is accrued on an hourly basis.
3. Multiply (1) and (2)

The mathematical representation is given in Appendix J.

3.4 Net Present Value (NPV) of Automation Program

The final step in developing the business case for an automation program involves bringing together the quantifiable benefits and costs of an automation program and calculating the NPV. A NPV calculation sums the discounted cash flows over a project to value it based on the present value of money. The formula is given in Equation (3-16) below.

$$NPV = \sum_{y=0}^Y \frac{CF_y}{(1 + DR)^y} \tag{3-16}$$

CF_y : Cash flow associated with year y

DR: Discount Rate

3.4.1 Discounting

Determining the appropriate discount rate depends on the specifics of an OEM and assumptions in the investigation. However, in general terms the discount rate is simply the ‘opportunity cost of capital’ an OEM foregoes by not investing the capital into another similar project of similar risk. [19] Furthermore, this investigation has established all cash flows in real rather than nominal terms, therefore the discount rate will follow suit in real terms and exclude inflation.

Many OEMs are large publically traded companies, or at least a large constituent of, and therefore, the after tax Weighted Average Cost of Capital (WACC) is a fair means to estimate a discount rate. Keep in mind, using after tax WACC as the discount rate requires the assumption that the projects market risk is similar to the rest of the OEM’s business. [20] The after tax WACC formula is shown in Equation (3-17).

$$WACC = r_D * (1 - Tax Rate) * \frac{D}{D + E} + r_E * \frac{E}{D + E} \quad (3-17)$$

r_D : cost of debt

r_E : cost of equity

D: market value of debt

E: market value of equity

Note: The market value of debt and equity can be found on a firm’s balance sheet. Financing a project with 50% debt is a fair first approximation.

3.4.1.1 Cost of Debt

The cost of debt is classified as the opportunity cost of the investors that hold a firm's debt. [20] It is calculated by taking the ratio of Interest Expense to Long Term Debt, both inputs are found in a firm's 10-K, see Equation (3-18).

$$r_D = \frac{\text{Interest Expense}}{\text{Long Term Debt}} \quad (3-18)$$

3.4.1.2 Cost of Equity

The cost of equity is more involved than the cost of debt and is classified as the opportunity cost of the investors holding a firm's shares. [20] The Capital Asset Pricing Model (CAPM) is used to find the cost of equity as it measures the risk premium associated with the nondiversifiable risk of a companies stock. The cost of equity is the risk free rate plus the risk premium and is shown below in Equation (3-19).

$$r_E = r_f + \beta_E(r_M - r_f) \quad (3-19)$$

r_f : risk free market rate.

r_M : market rate.

β_E : Beta of the security.

3.5 Summary

Quantifying the business case of introducing automation into a manual assembly line begins with gathering reliable data and establishing realistic assumptions. One of the most significant outcomes from Chapter 3 is the powerful effect learning has on a manual assembly line and the necessity to account for it through the Efficiency Factor when quantifying the labor hour savings from introducing automation. Chapter 3 further outlined the importance of understanding the

manufacturing costs of the OEM together with the Scope of Automation to allow for an educated estimate of the respective savings and costs due to automation.

The true savings quantified in this model include labor, quality, health & safety, depreciation, avoidable rate tooling, and manufacturing floor area. The true costs due to automation over an above the initial capital investment include operating costs and potential loss of revenue due to unforeseen breakdowns. The potential savings and costs are ultimately brought together in a discounted cash flow analysis that results in a NPV for the automation program. While the model outlined in this chapter has the potential to reveal significant insight into how different manufacturing inputs affect the net benefit of automation, without an effective implementation strategy the model's educational and financial potential will remain untapped. Chapter 4 introduced an implementation strategy that seeks to proactively engage the OEM.

Chapter 4 – Business Case Implementation

Strategy

This chapter outlines steps to integrate the business case model developed in Chapter 3 into a typical automation program bidding lifecycle. The discussion begins with an overview of a classic automation bidding lifecycle before exploring some challenges that could arise.

4.1 Automation Program Bidding Lifecycle

The aerospace assembly industry bidding process roughly follows the stages depicted in Figure 7. Each are detailed in the proceeding paragraphs.



Figure 7: Aerospace automation assembly program bidding lifecycle

1. **OEM internal investigation:** Before sending out RFIs to their suppliers, an OEM's operations and finance teams will use historical and current manufacturing data to determine a suitable budget and production schedule for an automation assembly program. During this initial study, the OEM will make assumptions regarding the level of automation and its associated impact to their current manual assembly line. In the case study presented in Chapter 5, the OEM estimates automation will reduce their T100 cycle time from about 3900 hours to just 1600 hours and achieve a maximum production rate of 13 ship sets per month. The resulting business case from the study is the key tool whereby a budget is estimated for the automation project. The internal business case is presented to the board of directors where funds required for the project are either approved for denied.

2. **Request for Interest (RFI):** A brief document is sent out to suppliers that summarize the scope of the project. Each supplier reviews the RFI and returns an automation concept coupled with a rough order of magnitude (ROM) price back to the OEM. **NOTE:** At this stage of the bidding cycle there is no requirement that individual communication between the OEM and supplier be shared amongst all suppliers.
3. **Review ROM Price:** The OEM reviews the interest of each supplier. This stage heavily depends on the perception an OEM Buyer has of each supplier. If there is sufficient interest, suppliers with a weak reputation will be excluded from the subsequent quoting stage.
4. **Request for Quote (RFQ):** A detailed document is sent out to all remaining suppliers. While this document is thorough, it is often a culmination of copy and paste sections from previous programs with a vast array of assumptions based on the OEM's limited working knowledge of the automation technology that will ultimately be applied. The suppliers review the document and return the same document with Agree/Disagree against each contractual requirement together with their formal quote to supply the automation.
5. **Review Quotes:** The OEM reviews each formal quote from a supplier. The bidding process in the aerospace industry is similar to a government contract bidding process—price and/or schedule is often king. Hence, if a quote from a supplier is not less than or at least close to the OEM's budgeted amount, it is eliminated without further review. If the quote price seems satisfactory, the OEM will review the supplier's Agree/Disagree statements to ascertain the supplier's level of agreement to the terms of the project, paying particular attention to production rates. Too many Disagree statements from a supplier and they run the risk of being thrown out of contention. **NOTE:** At this stage of the bidding cycle the rules of engagement shift to the requirement that all communication between the OEM and supplier (individual and collectively) be shared amongst all suppliers.
6. **Negotiate Statement of Work (SOW):** The few suppliers remaining now face negotiating the SOW. The SOW is a detailed document that encompasses the entire scope

of the project and contractual agreements that if not met are subject to liquidated damages. The SOW negotiation is a repetitive game that cycles between the OEM attempting to get commitments from the supplier and the supplier requesting more information before making a commitment.

7. **Award Purchase Order (PO):** Once the OEM is happy with their business case and the supplier's OEE commitment to deliver a level of automation performance, the supplier is awarded the PO.

When it comes to implementing the business case model, the critical issue to leverage from the above lifecycle is the change in rules of engagement post RFI stage. Thus, to capitalize on this window of secure communication, a supplier should engage an OEM using the business case model at or before the RFI stage. A supplier could take it a step further and approach OEMs who currently have manual assembly lines and propose the benefits automation will provide using the business case model. Though, overcoming organizational challenges, both within an OEM and automation supplier, is critical to implementing the business case model successfully.

4.2 OEM Organizational Challenges and Solutions

Perhaps the greatest challenge facing any organization implementing a new process is influencing and motivating the workforce to embrace change. The change management strategy for approaching an OEM with a new process that deviates from the status quo attacks the heart of the issue: an OEM's lack of automation experience and information.

4.2.1 Combating the Optimistic Implicit Bias

Certification requirements such as AS9100D, requires aerospace OEMs to document their production rates and other critical production metrics such as quality. This gives OEMs significant insight into the performance of their manual assembly line, particularly the learning curve rate. During an OEM's internal investigation as described in section 4.1, an OEM bids on

future production rates and cost targets to their customers further up the supply chain. As one might expect, to be competitive the production rates and cost targets are somewhat optimistic. The throughput and cost pledges are founded on the premise of learning: as they gain a better understanding of the assembly process they will be able to increase throughput while decreasing their manufacturing costs. A major consideration of an OEM in a production forecast is the Real Option of automating an assembly process in the future, allowing for a more competitive bid. Though, since an OEM has limited knowledge and experience with automating assembly processes, their automation assumptions run the risk of being unrealistically optimistic. To mitigate the optimistic implicit bias of an OEM with regard to automation, the Author proposes a proactive approach of engaging automation customers before the RFQ stage to build a trusting relationship and ensure OEM automation predictions are realistic.

4.2.2 Promoting a Symbiotic Information Sharing Relationship

Relationships between aerospace OEMs and their suppliers are often plagued by gamesmanship that results in the Nash Equilibrium of attempting to gain value out of the other with less given in return. The business case model developed in this thesis provides a vessel to drastically disrupt this dynamic. Due to the limited experience OEMs have in automation; they struggle to quantify the inherent benefit and consequently default to a price sensitive outlook. Now, however, a supplier can proactively approach an OEM with the business case model, engaging in productive discussions whereby information from both parties is combined into a single model to align all parties' intuition into the automation's quantifiable benefit. As a result, both parties will have a greater working knowledge and understanding of the benefits and limitations of automation. Perhaps the greatest advantage created from this engagement is the trust between both parties that will surely benefit both in future programs.

4.3 Summary

After the RFI stage in the bidding lifecycle all individual communication between the OEM and supplier must be shared amongst all suppliers. Therefore to leverage this shift in rules of engagement, a prudent supplier should solicit an OEM before the conclusion of the RFI bidding round in order to protect any competitive advantage they may have. While an OEM may have a thorough understanding of their manual assembly process, their lack of automation experience often results in optimistic expectations regarding the benefit automation will provide. Therefore, to enlighten OEMs and build a trusting relationship while maintaining confidentiality while bidding, a supplier should proactively approach an OEM with the business case model. While OEMs may justifiably be skeptical at first, they will arrive at a greater intuitive understanding by using the model as a catalyst for productive discussions. Accordingly, OEMs will discover and quantify the benefit of automation using their own production data adding credibility to the model's results.

Chapter 5 – Case Study

Building on the business case developed in Chapter 3 and the implementation strategy discussed in Chapter 4, this chapter explores a case study. The business case model is set against a potential automation program where an OEM's (Company X) current manual assembly line assembles two fuselage sections for a regional jet manufacturer (Company Z). This chapter briefly outlines the project and investigates the results.

5.1 Understanding the Current State

Company X is a knowledgeable airframe manufacturer although is relatively inexperienced with regard to automation. The contract is to provide two fuselage sections to a regional jet manufacturer (Company Z). Company X approached Ascent with the intent to implement automation at the 20th ship set (SS₂₀)—at the time they had just completed SS₁₀ through a fully manual assembly process. At close to half the price of the nearest competitor and within Company X's budget, Ascent would supply and integrate both tooling and automation required to encompass the SOW. There was one major sticking point, however, the production rates Ascent predicted with automation installed were only half that of what Company X had assumed in their original proposal to Company Z. Ascent worked closely with Company X to understand their current process needs to establish a business case that satisfied production and financial expectations. Company X currently has a firm order of 600 ship sets with an option for a further 1400.

5.2 Capturing Reliable Data

As expected Company X was wary of Ascent's production prediction and were initially skeptical of the business case model. However, as Ascent continued their good faith efforts to understand Company X's needs, trust between both companies continued to grow.

5.2.1 Manual Assembly Learning Curve

As stated in section 5.1, Company X had just completed SS₁₀ (consuming just over 8000 production hours) with the hope to install automation at SS₂₀. Company X's PPDs estimated T100 (SS₁₀₀) would consume about 3900 manual assembly hours without automation installed. Extrapolating back along the industry standard 85 percent learning curve, SS₁₀ was estimated to consume 8000 production hours—tracking close enough to current production. During contract negotiations with Company Z, Company X assured Company Z they would be able to produce 13 ship sets per month (termed 'Rate 13') by SS₁₀₀. According to this agreement, Company X assumed automation would reduce SS₁₀₀'s total production hours to less than 1600 hours instead of 3900—close to a 60 percent decrease as presented by the dashed line in Figure 8.

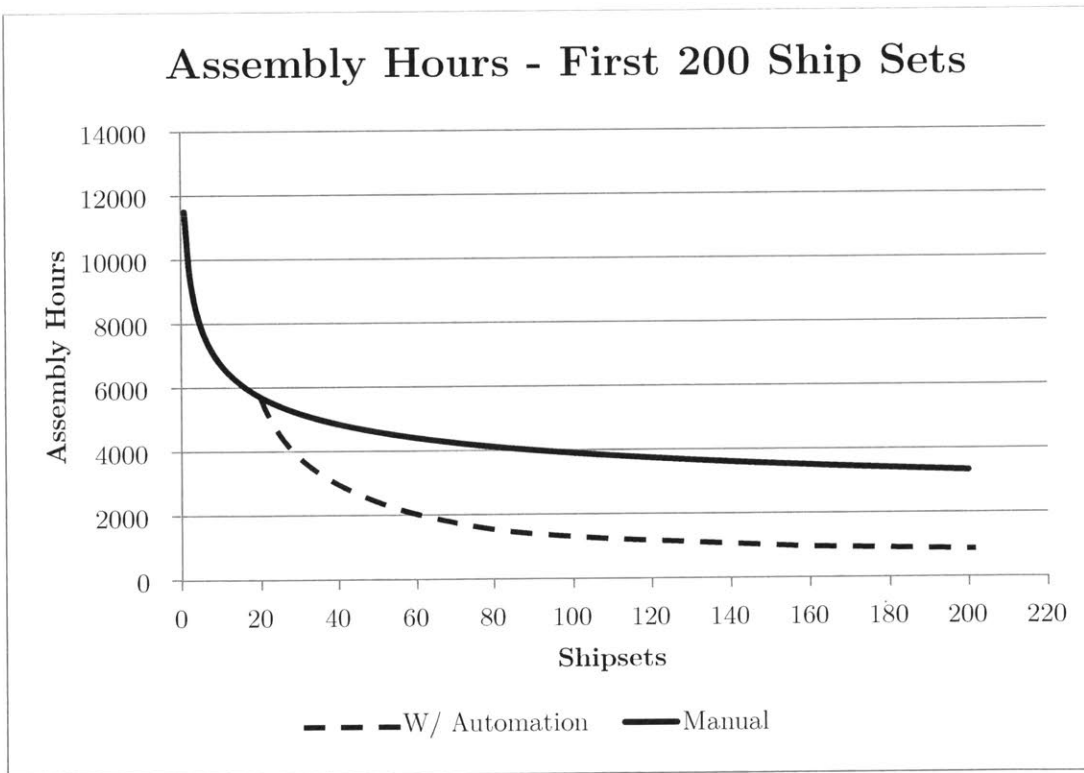


Figure 8: Production learning curve, both with and without automation installed

The dashed line in Figure 8 demonstrates the level of optimism Company X had for the benefits automation would provide. If implemented at SS₂₀ Company X assumed the production learning curve would alter to track the dashed line, arriving at about 1600 production for SS₁₀₀.

Company X arrived at 1600 hours partly out of necessity to remain competitive in their bid to Company Z but also from an optimistic assessment of the automation's SoA₁₀₀ as we will explore in the next section.

5.2.2 Scope of Automation

Evaluating Company X's PPDs per the method described in section 3.1.4 Ascent estimated the SoA₁₀₀ to be 910 hours out of a possible 3900 hours, corresponding to about 23 percent of manual labor hours. What is alarming about this figure is that it is far less than the 60 percent decrease Company X predicted. Thus, even if every assembly hour within the SoA₁₀₀ were eliminated due to automation the production line would still fall 1390 hours (36 percent) short of their projected target for Rate 13.

5.2.3 Labor Hour Savings

Recalling section 3.2.1, after assessing each assembly category within the SoA₁₀₀ the potential labor hour savings of SS₁₀₀ (*TLHS*₁₀₀) totaled 623 hours. Based off Ascent's estimate in section 3.2.1.2, the automation integration period for this program was conservatively assumed to take 20 ship sets (ship set 20 to ship set 40) leading to the potential labor savings given in Figure 9.

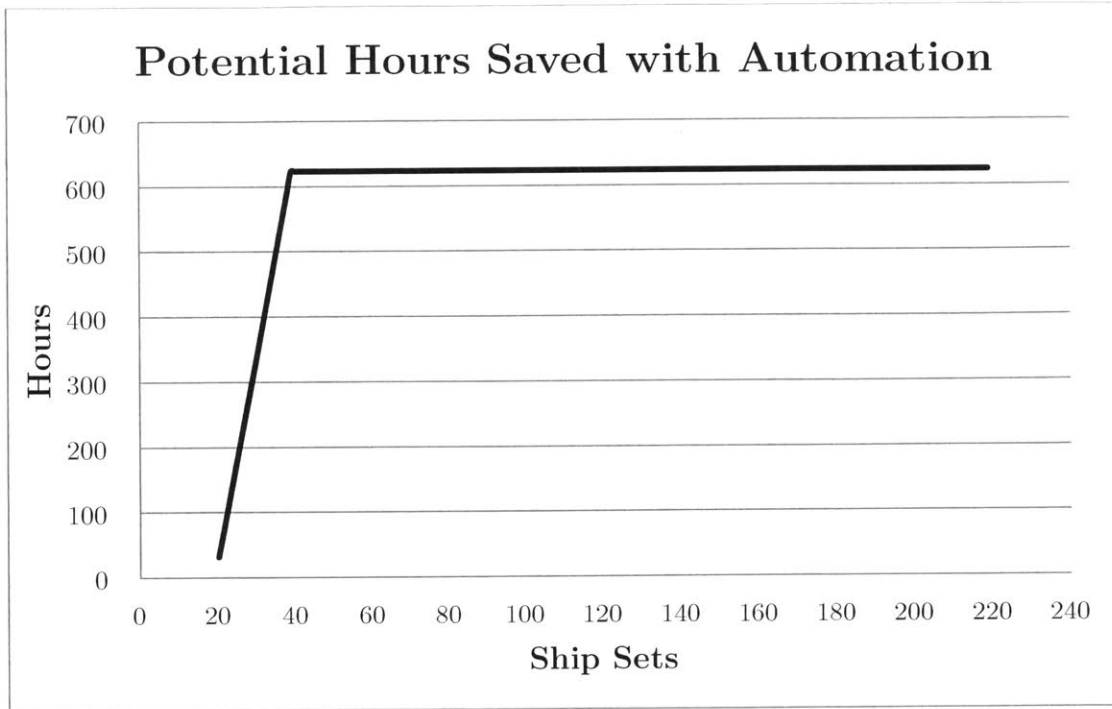


Figure 9: Total labor hours saved with automation

However, as discussed in section 3.1.2, the potential labor savings will be subject to an Efficiency Factor (EF_n) defined in Equation (3-8) as:

$$EF_n = \left(\frac{n}{100}\right)^b$$

From Equation (3-1) and unit learning theory we can calculate the value of H_1 based on SS_{100} and an 85 percent learning curve:

$$H_n = H_1 n^b = H_1 n^{\log_2(\xi)} = H_1 n^{\log_2(0.85)} = H_1 n^{-.234}$$

Rearranging and substituting for SS_{100} :

$$H_1 = \frac{H_n}{n^{-.234}} = \frac{H_{100}}{100^{-.234}} = \frac{3900}{100^{-.234}} = 11,500 \text{ hours}$$

Therefore:

$$EF_n = \frac{11,500}{3900} n^{-0.234} = 2.94n^{-0.234}$$

See Figure 10 for a depiction of EF_n over the first 200 ship sets.

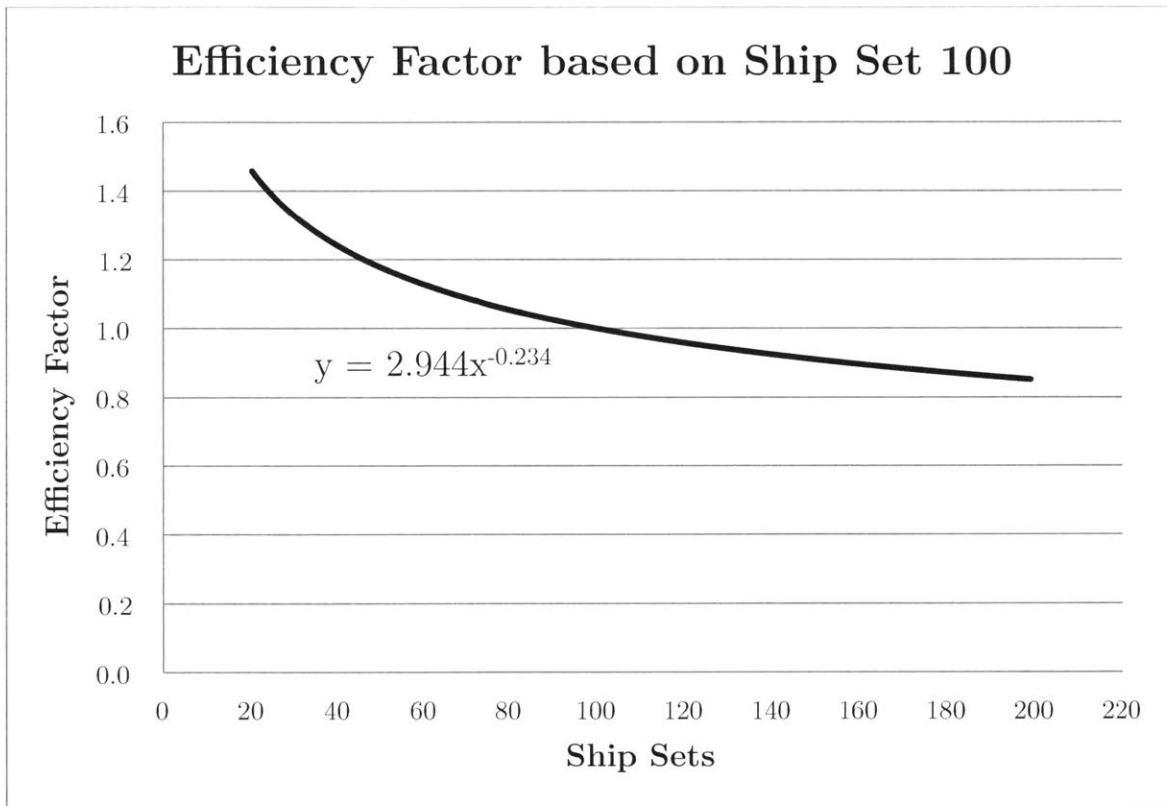


Figure 10: Efficiency Factor per ship set for Company X at 85 percent learning curve

Revisiting Equation (3-13), if the data from Figure 9 ($TLHS_n$) and Figure 10 (EF_n) are multiplied together the result is the actual labor hours saved ($ALHS_n$) per ship set. Figure 11 and Figure 12 demonstrate the $ALHS_n$ for the first 200 ship sets and the entire program (2000 ship sets) respectively.

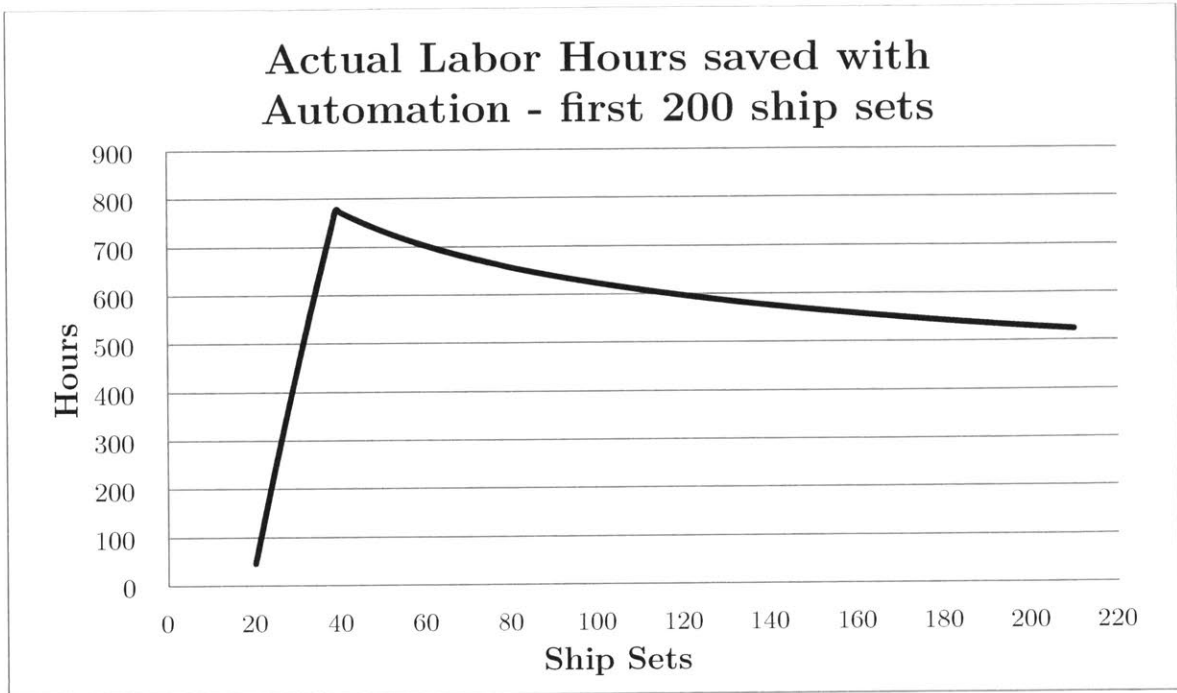


Figure 11: Actual labor hours per ship set for first 200 ship sets

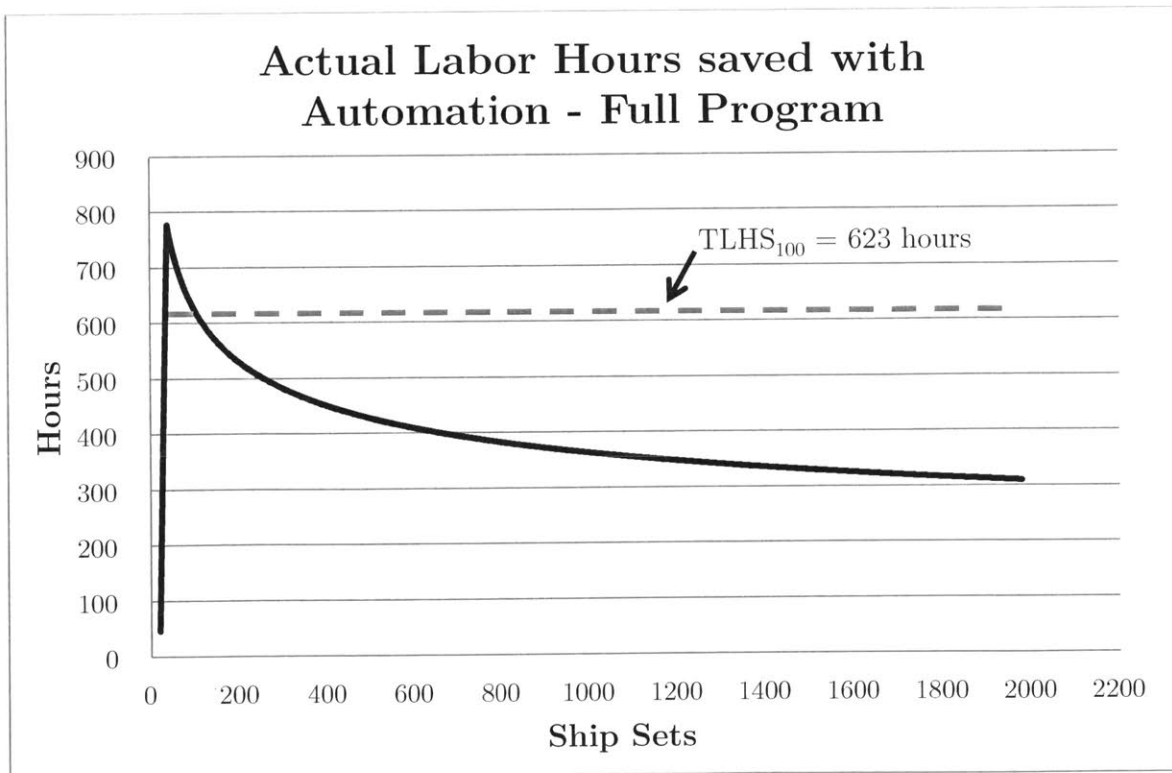


Figure 12: Actual labor savings per ship set for entire program

Figure 12 clearly demonstrates the power of manual assembly learning. For most of the program the $ALHS_n$ are less than the $TLHS_{100}$ of 623 hours calculated for SS_{100} . Furthermore, according to the above analysis, the program still faces the issue of running 1390 hours over Company X’s anticipated 1600 production hours for SS_{100} , see Figure 13.

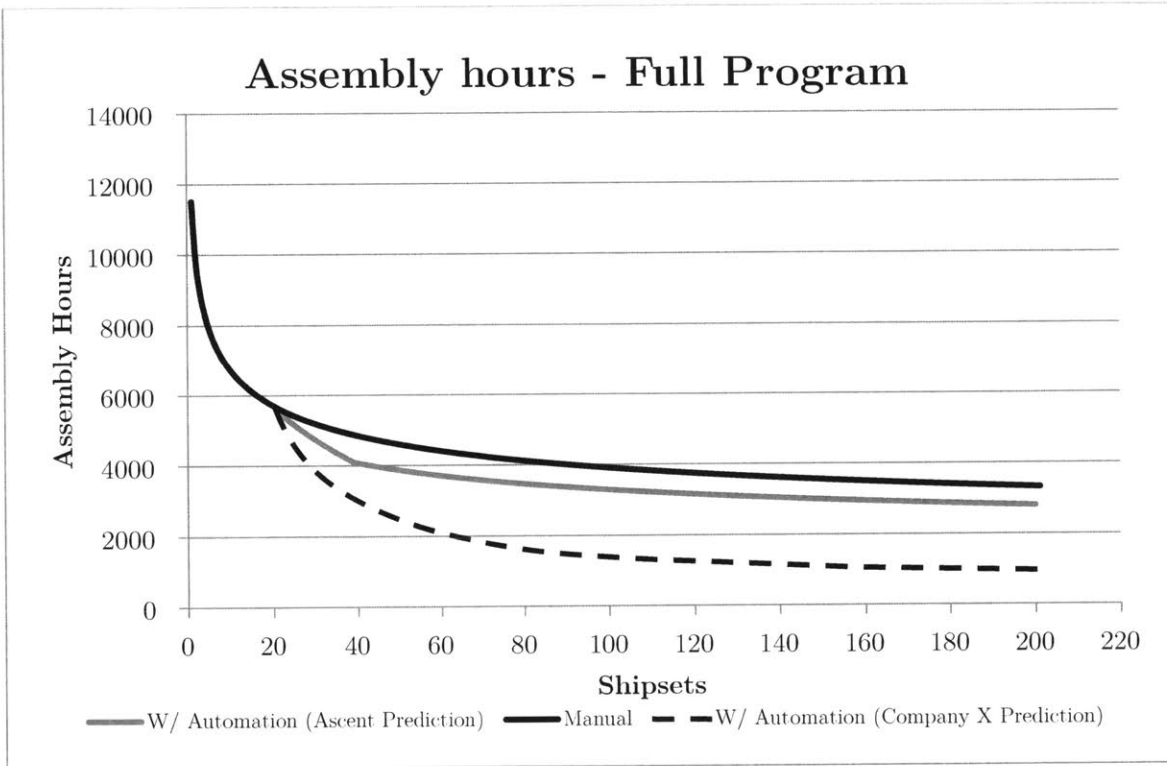


Figure 13: Predicted Assembly Hours with Automation – Ascent and Company X

Figure 13 illustrates the stark difference in labor saving estimates between Ascent and Company X. The disparity stems from an OEM’s optimistic estimate of their SoA_{100} —that is, they overestimate the number of assembly stages that are viable automation candidates. The OEM’s optimistic outlook may also derive from competitive production schedule bidding to win a contract.

Ascent reduced labor hours further by reevaluating the assembly lines material handling and CoS. Material handling modifications included rearranging the production line and introducing casters to tooling. This allows greater flexibility in the production line and less tooling changeovers, reducing the production hours by a further 700 hours. Company X pushed more CoS

onto their suppliers who had lower labor rates resulting an increase in material costs with a corresponding larger reduction in labor costs. This produced a net decrease in overall manufacturing costs and a further decrease of 500 production hours, bringing the total production hours for SS₁₀₀ close to their 1600 hour target.

5.3 Results and Discussion

Based on an initial automation investment of \$12M, labor hour savings estimated in section 5.2.3, and Company X’s manufacturing data given in Appendix C the results of the business case for Company X are revealed in Table 2.

Table 2: Results of Company X Business Case Investigation

| Summary | |
|--|----------------|
| Net Present Value (Firm Order – 600 Ship Sets) | |
| Projected NPV | \$16.3M |
| Net Present Value (Full Program – 2000 Ship Sets) | |
| Projected NPV | \$26.5M |
| Internal Rate of Return (IRR) | 56% |
| Discounted Payback Period | 1.6 years |
| Discount Rate (WACC) | 8.11% |
| Total Discounted Savings (Full Program) | |
| Labor | \$40.0M |
| Quality | \$15.2M |
| Health & Safety | \$0.1M |
| Depreciation Tax Credit | \$3.3M |
| Avoidable Rate Tooling | \$7.3M |
| Total Discounted Costs (Full Program) | |
| Operating Costs | \$5.3M |
| Downtime Costs | \$21.8M |

Table 2 reveals that labor hour savings are by far the greatest benefit from introducing automation to a manual assembly line, followed by quality and avoidable rate tool savings.

Interestingly the savings from increased Health & Safety were negligible. Nevertheless, one must also consider in the tangible psychological benefit of eliminating mind-numbing repetitive labor. The above analysis excludes the benefit of floor space savings, as quantifying this benefit is non-trivial, yet the potential magnitude of its benefit demands consideration. A preliminary analysis showed this benefit for Company X increases the discounted operating profit by about \$200 million over the life of the program.

Apart from the initial automation investment of \$12M, the most substantial total discounted cost arose in the form of potential losses in operating profit as a result of unexpected downtime. This case study investigation took a conservative standpoint by using the maximum tolerated downtime of two percent, while typical unexpected downtime is only half a percent. Ascent’s historical data revealed an average operating cost of \$5,000 per ship set leading to a total discounted operating cost of \$5.3M over the full program.

One of the most intriguing insights is how the program’s discounted cash flow savings vary with respect to the program’s production schedule, refer to Figure 14.

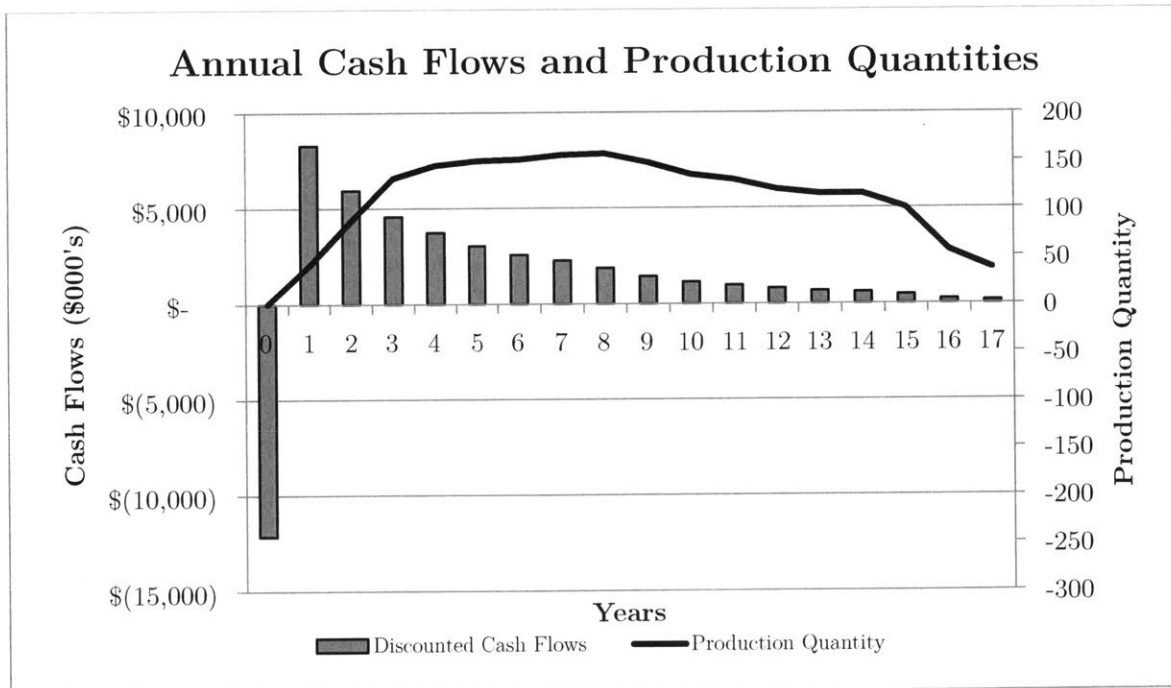


Figure 14: Discounted cash flows and production schedule over entire program

Figure 14 uncovers how the annual discounted cash flows due to the benefits of automation vary with production quantities. The benefits from automation are most impactful earlier in the program for two reasons: 1) discounting and 2) learning effects reducing the impact of automation. Thus, automation should be implemented early in a project to extract maximum benefit. Figure 15 depicts how the program cash flows are affected by eliminating: 1) discounting [blue bars], 2) learning effects [red bars], and 3) both discounting and learning effects [green bars] respectively.

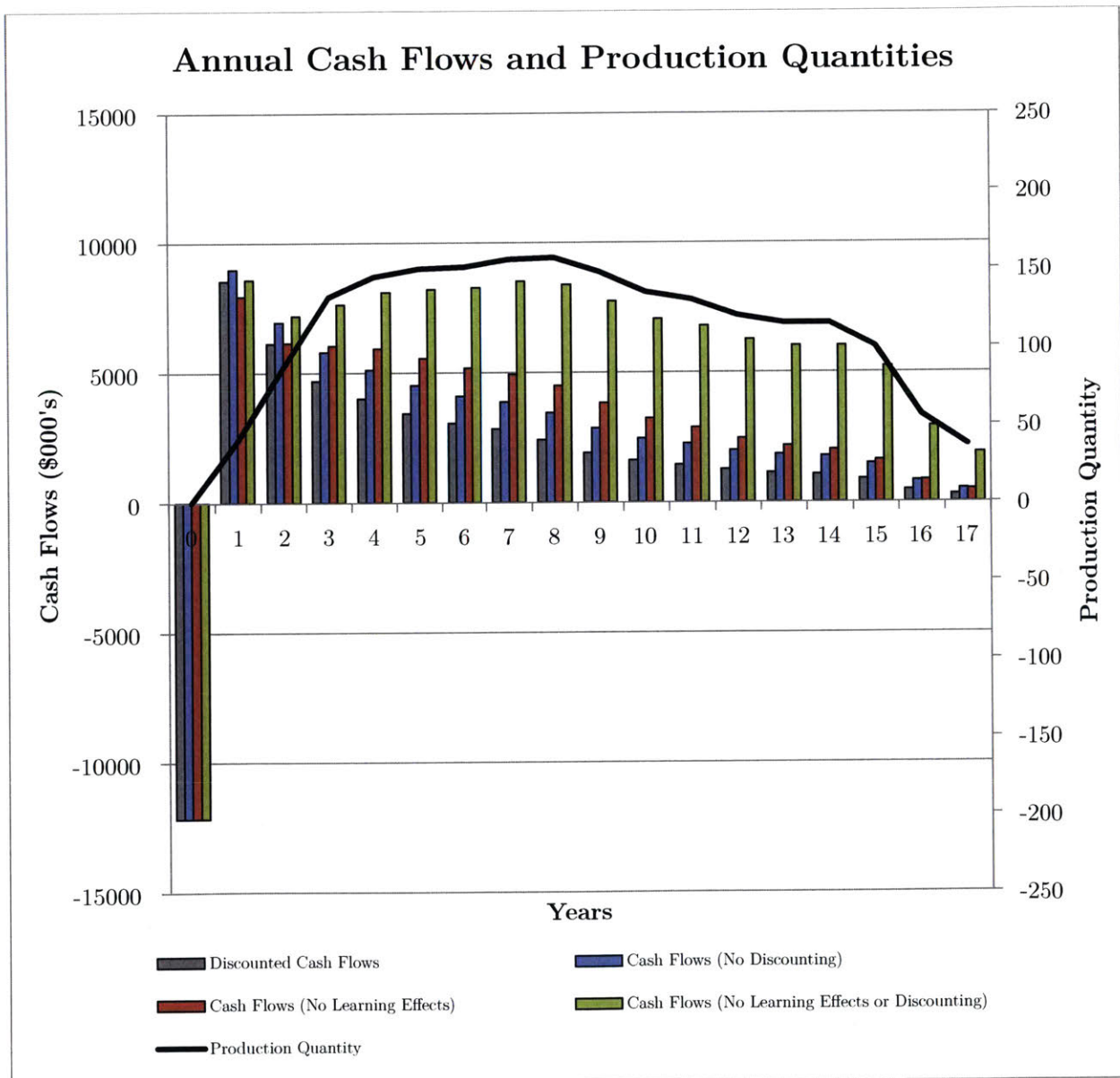


Figure 15: Annual cash flows demonstrating the effects of discounting and learning

Figure 15 demonstrates the impact both discounting and learning have on the quantifiable benefits automation provides to a current manual assembly line. Interestingly, in this case study learning effects had a greater impact than discounting even though the discount rate was a modest 8.1 percent. Reviewing Figure 14, however, highlights the savings from avoidable rate tooling captured in the first two years of production. The savings in the first 2 years are uncorrelated with the rest of the savings data and occurs during production ramp up. This is a consequence of the inter-relationship between ramping up production while the manual labor force is inexperienced (still high up the learning curve). This is driven by an ambitious production schedule, demanding ramp up to increase throughput. The repercussion is further capital investment into rate tooling to accommodate the added manpower to achieve the required throughput. For interest sake, Figure 16 shows the effect of eliminating Rate Tool savings from the discounted cash flow analysis.

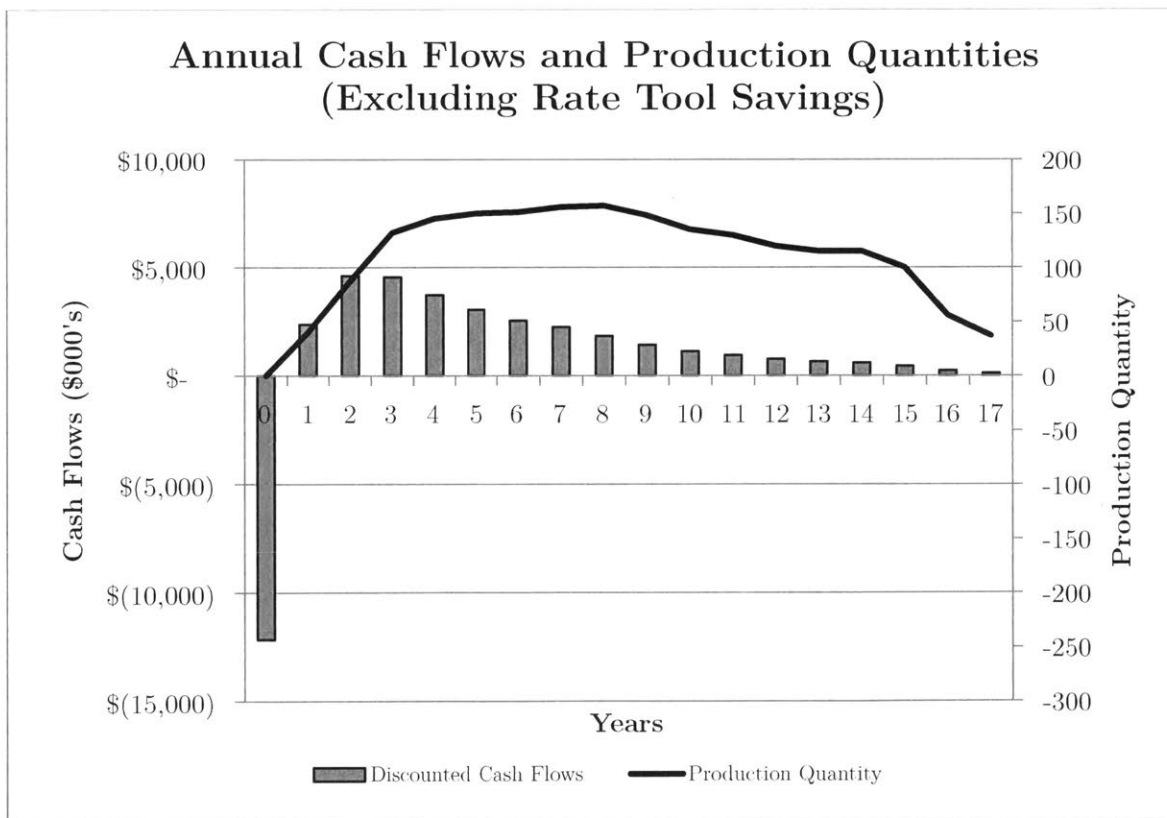


Figure 16: Discounted cash flows and production schedule without Rate Tool savings

5.4 Summary

An OEM (Company X) is 10 ship sets into a 2000 ship set program and is looking to automate their manual fuselage assembly line. Company X predicts T100 will consume 3900 labor hours and anticipate automation will reduce this by over 60 percent to little over 1600 hours. After reviewing Company X's PPDs, Ascent on the other hand, only predicted about a 16 percent labor hour saving of 623 hours coming from automation at T100. The 1600 hour target was achieved through further labor saving efforts of material handling and increasing the OEMs CoS. The largest automation benefits manifested in labor (\$40M), quality (\$15M), and avoidable rate tooling (\$7M). Contrasting this with a conservative estimate of the total anticipated operating and downtime costs at about \$27M. Ultimately, without accounting for further savings such as material handling, the \$12M automation project is set to achieve a positive NPV of about \$27M over the life of the program. Apart from this positive result, another interesting take away is the massive effect discounting and [to an even greater consequence] the learning effects have on the future cash flows. Thus, to extract maximum benefit from automation, it is advantageous to implement automation into a manual assembly line early in a program after production has progressed to a point where the PPDs are stable.

Chapter 6 – Conclusion

This thesis presents a method whereby OEMs and suppliers can quantify the financial benefits and limitations automation can provide to a manual fuselage assembly line. The case study of Company X presented in Chapter 5 clearly reveals how the financial benefits can out way the costs with the greatest and most tangible benefit of automation arising from labor savings. Yet, as highlighted in sections 3.1.1 and 3.1.2, labor savings need to account for the learning effects of the alternate scenario of a purely manual assembly line. Furthermore, learning theory also demonstrates the necessity to implement automation into a manual assembly line early in the program to extract maximum benefit from the automation. Ideally manual production should progress to a point where it is possible to develop effective PPDs for T100 yet still allow enough time to implement automation before production ramp up. This could potentially save millions in rate tool capital expenditure alone.

Finally, any return on investment analysis should always be viewed with skepticism. While many interdependent variables were introduced in this study, effective information sharing between OEMs and suppliers that allow for accurate data capture is crucial to minimizing ambiguous expectations and increasing the accuracy of an automation business case. To mitigate the optimistic implicit bias of an OEM with regard to automation, this thesis suggests an automation supplier proactively engage OEMs with the financial model during or before the RFI stage. RFI is most opportune for a supplier as there is no requirement to share communication amongst other bidding parties. This proactive approach also affords OEMs and suppliers time to trial different production scenarios through the business case model, deepening each stakeholder's intuition into the applicability and limitations of automation, ultimately leading to a more effective production line.

Chapter 7 – Recommendations for further study

The theoretical assumptions and limitations of this investigation are fertile ground for opportunities of further study. Two particular areas of further study are 1) accounting for uncertainty with respect to model assumptions and data inputs, and 2) the effects of production schedule smoothing on overall profitability for the OEM.

7.1 Accounting for Uncertainty

Any business case model is only as accurate and realistic as the input data and assumptions that pertain to it. Due to numerous variables, and hence, many sources for error, it is impossible to truly know how accurate a model is without accounting for uncertainty and its cumulative effect on the model's result. Accounting for uncertainty is no simple task, though one should first prioritize accounting for the uncertainty of inputs that have the greatest influence, such as the learning curve that is used to estimate the labor hours saved.

There is much empirical data that suggests manual assembly lines (particularly in airframe assembly) follow a learning curve. Massive error can arise if the learning curve of an assembly line is incorrect, principally estimating H_1 and learning rate (ξ). [15] As we saw in Equation (3-1), H_1 is a multiplier. Thus, any percentage error in estimating H_1 manifests in the same percentage error for the n^{th} unit of production. Quantifying the error in ξ is slightly more involved. Below is a derivation to quantify the error attributed to every one-percentage point error in ξ .

Recall H_n and b that were defined in Equations (3-1) and (3-5):

$$H_n = H_1 n^b$$

$$b = \log_2(\xi)$$

For demonstration, let's say when selecting ξ we erroneously select A, yet the actual ξ is C, the corresponding error (ξ_{Error}) with respect to each ship set n is given in Equation (7-1) and simplified in Equation (7-2).

$$\xi_{Error} = \frac{H_1 n^{\log_2(A)}}{H_1 n^{\log_2(C)}} \tag{7-1}$$

Simplifying:

$$\xi_{Error} = n^{\log_2\left(\frac{A}{C}\right)} \tag{7-2}$$

For example if the correct ξ is 85 percent but we instead select a ξ of 86 percent, the error with respect to n is shown below and in Figure 17.

$$\xi_{Error} = n^{\log_2\left(\frac{86\%}{85\%}\right)} = n^{\log_2(1.0118)} = n^{0.017}$$

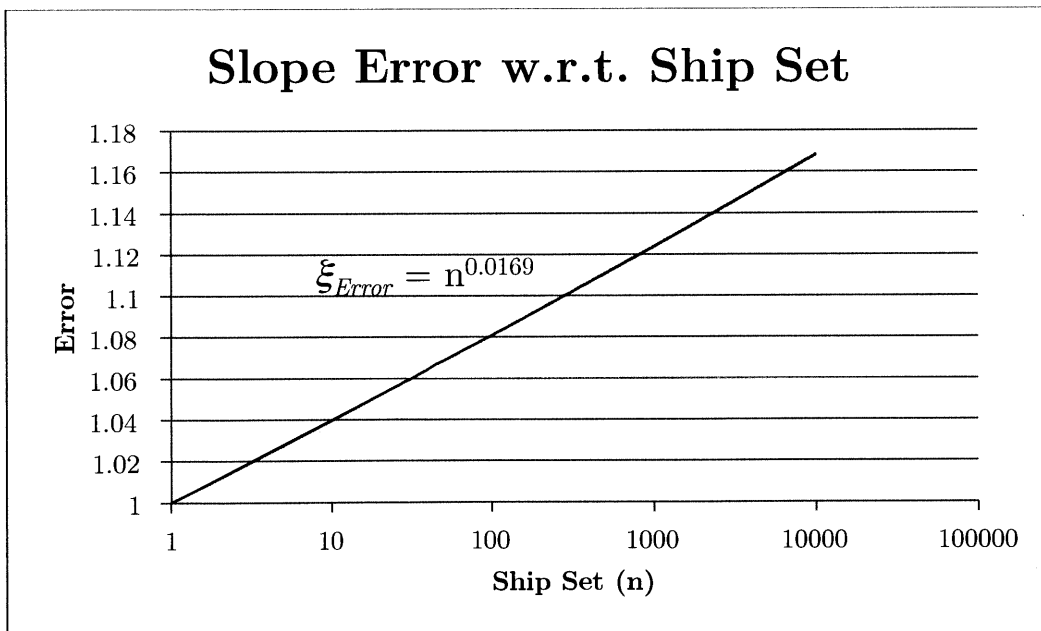


Figure 17: Resulting slope error from one percentage point learning rate error

Thus, for every one-percentage point error in ξ results in a change in b of about 0.017. This correlates to a 4% error in labor hours for the 10th ship set, 8% error for the 100th ship set, and 12% error for the 1000th ship set.

The cumulative error of H_1 and ξ is additive. [15] For example, if H_1 is estimated at 10% too high and the learning rate is also estimated at one-percentage point too high the total error would be 22% at the 1000th ship set. Conversely, if H_1 is estimated at 10% too low and the learning curve is still estimated at one-percentage point too high the total error would instead be two percent at the 1000th ship set. [15]

7.2 Production Smoothing

Another opportunity for future study is the effect production smoothing has on the overall profitability of an aerospace assembly program. This may or may not involve an automation program as production smoothing could eliminate the need for rate tooling, reducing the potential benefit of automation but increasing the profitability of an OEMs assembly program overall.

The main advantage of production smoothing is the steady ramp up production while retaining the same workforce for the entire program. This captures knowledge and preserves learning within the assembly team, potentially speeding up learning cycles and hence ensuring the labor force continues down the learning curve. If labor turn over is high within an assembly line the rate of learning will decrease and may in fact become higher than 100% (forgetting). One means to introduce production smoothing is keeping the headcount constant year over year and fashioning the production schedule based on the available production hours per year. The production schedule will vary based on the headcount constraint and where production is currently tracking on the assembly learning curve.

The production schedule of the case study in section Chapter 5 (Scenario A) is shown below in Figure 18.

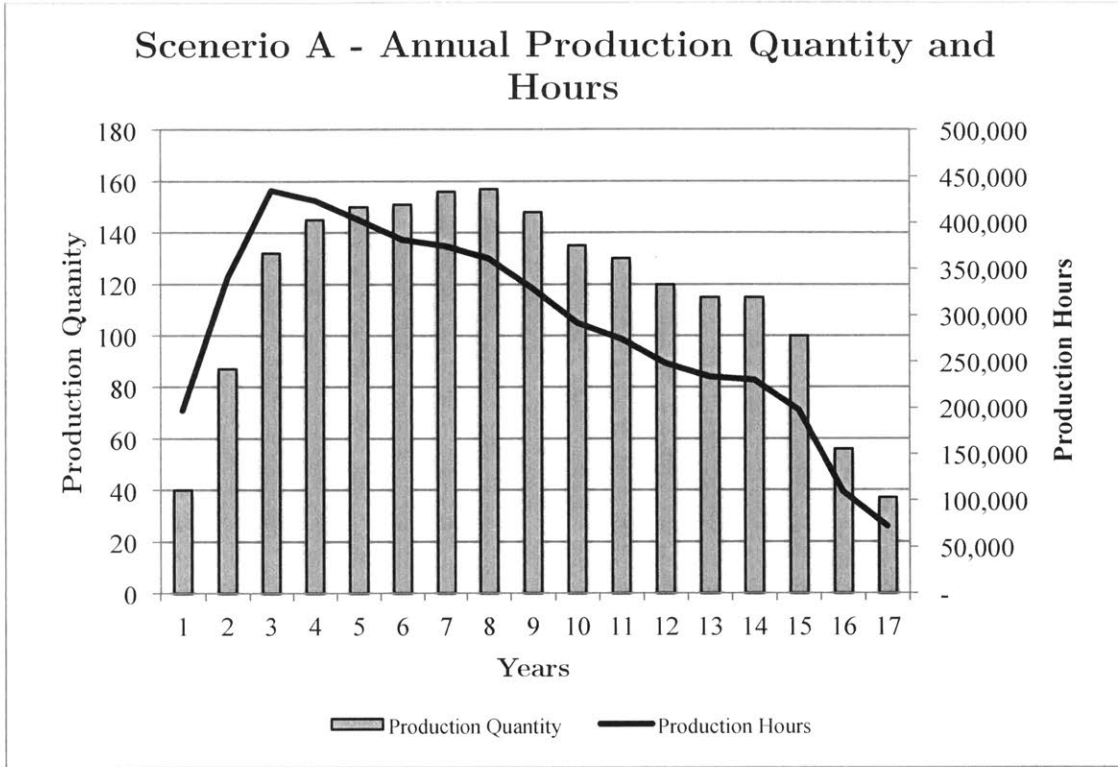


Figure 18: Production schedule for OEM in case study without production smoothing

Figure 18, unmistakably demonstrates the labor allocation inefficiency of the OEM’s current production schedule. In the current state, production ramps up steeply while the labor force is inexperienced. As a result, the annual production hours are subjected to growing pains, peaking in year three and steadily decreasing for the rest of the program. Accordingly, mechanics that absorbed resources and time to learn the process are now allocated to other programs with the assembly knowledge and learning leaving with them. A more efficient allocation of labor resources is to keep the same workforce on the assembly line for the entire program (Scenario B) as shown in Figure 19.

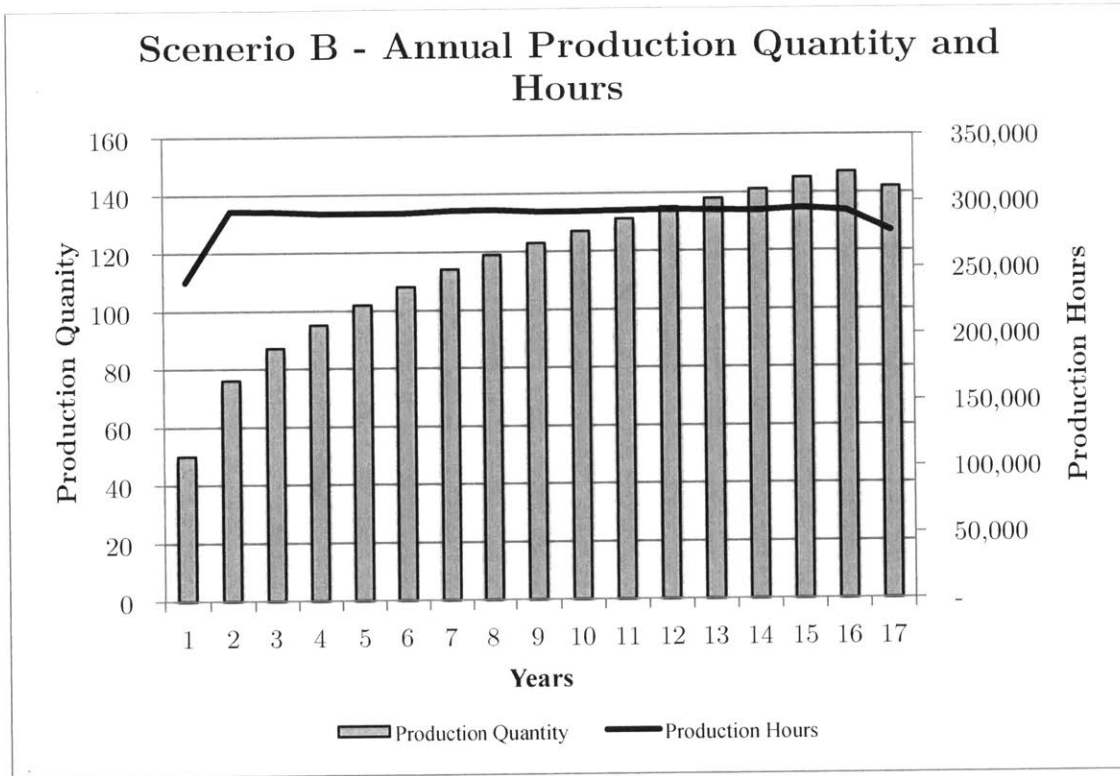


Figure 19: Production schedule for OEM in case study with production smoothing

In Scenario B, production ramp up is more controlled and ensures learning is retained within the same assembly line. The obvious downside to a steady production ramp up is the lower throughput in the early years of the program, which may not be acceptable to an OEM’s customer further up the supply chain. This presents the opportunity for a hybrid solution where there is still moderate ramp up that satisfies the supply chain yet also seeks to maximize knowledge retention within an assembly line.

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Appendices

Appendix A – Nomenclature

Note: Variables in bold are matrices.

| | |
|------------|---|
| A | Erroneous learning rate |
| ADC_y | Automation Downtime Cost for a given year y |
| $ALHS_n$ | Actual Labor Hours Saved due to automation for ship set n . This quantity accounts for the learning effects happening in the alternate scenario of a purely manual assembly process |
| AT_n | Automation Assembly Time for ship set n |
| $Avg.EF_y$ | Average Efficiency Factor for a given year y |
| AX | Assembly Category |
| b | The ‘Natural Slope’ (power law exponent) of a learning curve |
| C | Actual learning rate |
| CT | Cycle Time |
| D | Market value of Debt |
| E | Market value of Equity |
| $EBIT_n$ | Earnings before Interest and Taxes gained per ship set n |
| EF_n | Efficiency Factor for ship set n |
| FX_{AX} | Fastener Count for assembly category AX |
| H_n | Total Assembly Hours required to assemble the n^{th} ship set of production |
| $HX_{S,y}$ | Required Headcount of mechanics at a given assembly station S in a given year y |

| | |
|---------------------------------|---|
| $H\&SS_y$ | Annual Health & Safety savings |
| i | Work Instruction number |
| I | Total number of WIs that are within the Scope of Automation |
| \overline{IC} | Average Injury Cost |
| $InDC$ | Indirect Costs |
| IR | Injury Rate: number of injuries per million labor hours |
| $IRedR$ | Injury Reduction Rate: since injuries are not fully eliminated |
| LC_n | Labor Costs per ship set n |
| \overline{LC} | Average Labor Cost for program |
| LHS_n | Labor Hour Savings for ship set n |
| LS_y | Monetary Labor Savings for all ship sets within a given year y |
| MAT_i | Manual Assembly Time for Work Instruction i |
| $MaxHX_S$ | Maximum Headcount for each assembly station S |
| MCT_{AX} | Standard Manual Cycle Time for assembly category AX |
| $MtlC$ | Material Costs |
| n | Ship set number |
| N | Total number of unites (ship sets) in a program |
| OH_n | Overhead Costs for ship set n |
| PQ_y | Production Quantity: Number of ship sets produced in year y with respect to the production schedule |
| PS_y | Number of produced ship sets in year y with respect to the production schedule |
| r_f | Risk free market rate. |

| | |
|-------------------------------------|--|
| r_M | Market rate. |
| r_D | Cost of Debt |
| r_E | Cost of Equity |
| RAR_y | Revenue Accrual Rate for a given year. |
| $RedR$ | Rework and Scrap Reduction Rate: since rework and scrap are not fully eliminated. |
| Rev_n | Revenue from the n th ship set |
| RR_y | Required Production Rate (monthly basis) in year y |
| RS | Rework Scope: Scrap and rework is only reduced from tasks that are performed by automation |
| S | Assembly Station |
| SoA_n | Scope of Automation for ship set n |
| $SoA_{100_{AX}}$ | Scope of Automation at T100 within an assembly category AX |
| \overline{SRR} | Average Scrap and Rework Rate |
| SS_n | Ship Set n |
| T_y | The Total Tooling required per year y |
| $TAAT_n$ | Total Automated Assembly Time for ship set n |
| \overline{TDMC} | Average Total Direct Manufacturing Costs |
| $TDMC_n$ | Total Direct Manufacturing Costs for ship set n |
| $TF_{S,y}$ | Tooling Factor: scales the tooling investment at a given station in a given year |
| $TInst_y$ | Level of Tooling Installed for a given year y |
| $TIncr_y$ | Tooling Increase for a given year y |
| $TLHS_n$ | Total Labor Hours Saved for ship set n |

| | |
|----------------|--|
| TMC_n | Total Manufacturing Cost for ship set n |
| TT_n | Manual fastener taking time for ship set n |
| TQS_y | Total Quality Savings per year y |
| y | Year within program since implementing automation |
| Y | Total number of years of program |
| z | Total number of Assembly Stations |
| α_{AX} | Number of automated fasteners within an assembly category AX |
| β_{AX} | Number of manually tacked fasteners within an assembly category AX |
| β_E | Beta of the security: measure of the specific systematic risk |
| γ_{AX} | Number of total fasteners within an assembly category AX |
| ε | Average Production Productivity rate |
| η | Machine Failure rate (%) |
| $\theta_{S,y}$ | Production hours required at a station s for a given year y |
| κ_{AX} | Percent of automated fasteners within an assembly category AX |
| μ | Number of ship sets required to fully integrate automation |
| ξ | Learning Rate (%) |
| ξ_{Error} | Error from selecting the incorrect learning rate |
| Π_S | Production hours per assembly station S for T100 |
| ρ_y | Quality Savings per year y |
| σ_y | Scrap Savings per year y |
| ϕ | Annual available production hours per year |

ω Available monthly production hours per employee

Appendix B – Minimum Data List Required for Business Case Model

Using historical data in combination with an OEM's Request for Interest (RFI), the model can provide a rough order of magnitude expected return on investment to any OEM. The data required is as follows:

1. Scope of Work:
 - i. Number and type fasteners to be installed
 - ii. Installation categories (e.g. Skin Seam, Shear Tie to Airframe, etc.)
 - iii. Annual production schedule with associated maximum headcount
2. Current manual assembly process:
 - i. How many (n) ship sets are complete
 - ii. How many production hours did the nth ship set consume
 - iii. Planned automation implementation ship set
 - iv. PPDs: What ship set the production planning documents are set against and how many production hours that ship set will consume
3. Manufacturing Cost Inputs:
 - i. Percentage distribution of manufacturing costs:
 1. Labor
 2. Material
 3. Other
 - ii. Labor rate
 - iii. Overhead rate
4. Scrap/Rework Inputs:
 - i. Average scrap and rework rates
5. Health & Safety Inputs:
 - i. Average number and cost of injuries per million production hours
6. Maximum allowed automation down time
7. Available annual production hours per employee
8. Discount rate

Appendix C – Case Study Inputs

1. Scope of Work:
 - i. Number and type fasteners to be installed: 20,000 Rivets
 - ii. Installation categories:
 1. Longitudinal and Circumferential Skin Splices
 2. Shear Tie to Airframe
 3. Shear Tie to Aircraft Skin
 4. Door Surrounds
 - iii. Annual production schedule with associated maximum headcount
 1. See Figure 18
2. Current manual assembly process:
 - i. How many (n) ship sets are complete: 10
 - ii. How many production hours did the nth ship set consume: 8000
 - iii. Planned automation implementation ship set: 20
 - iv. PPDs: What ship set are the production planning documents are set against and how many production hours that ship set will consume: SS₁₀₀ and 3910 hours
3. Manufacturing Cost Inputs:
 - i. Percentage distribution of manufacturing costs: NOTE: Since Company X increased their CoS and pushed preassembly onto their suppliers, labor and material percentages differ from section 3.1.3.1:
 1. Labor: 40%
 2. Material: 50%
 3. Other: 10%
 - ii. Labor rate: \$90/hour
 - iii. Overhead rate: 20%
4. Scrap/Rework Inputs:
 - i. Average scrap and rework rates: 10%
5. Health & Safety Inputs:
 - i. Average number and cost of injuries per million production hours: four
6. Maximum allowed automation down time: 2%
7. Available annual production hours per employee: 2080
8. Discount rate: 8.1%

Appendix D – Equations: Establishing the Manufacturing Costs

For this investigation we will only focus on OEM product costs related to manufacturing. Consequently the manufacturing costs for our investigation can be divided into two general categories: Direct and Indirect product costs:

$$MC = DC + InDC \quad (D-1)$$

MC: Manufacturing Cost

DC: Direct Cost

InDC: Indirect Cost

D.1 Direct Costs

Direct costs are costs that directly relate to manufacturing the product such as direct labor, raw material, and other engineering related activities.

$$DC = LC + MtlC + OC \quad (D-2)$$

LC: Labor Costs

MtlC: Material Costs

OC: Other Costs

DC's associated with fuselage manufacture are typically allocated as follows:

- Labor Costs (LC): 70%
- Material Costs (MC): 20%
- Other Costs (OC) [quality assurance, recurring engineering and tooling]: 10% [16]

Above are generic estimates. The specific allocations to an OEM's direct manufacturing costs may differ. At the outset of an automation program there is little or no visibility into an OEM's manufacturing costs other than their production learning curve metrics. The value of the cost distribution assumption above allows us to estimate the total direct manufacturing costs for any ship set ($TDMC_n$) using labor hours as a proxy. We begin by finding the average labor costs per ship set of the entire program (\overline{LC}).

$$\overline{LC} = \left(\frac{\sum_{n=1}^N H_n}{N} \right) * LR \quad (D-3)$$

\overline{LC} : Average labor cost for program

LR : Labor Rate

Since we assumed that the \overline{LC} of a fuselage accounts for about 70% of the DC's, we can extrapolate to the average total direct manufacturing cost (\overline{TDMC}):

$$\overline{TDMC} = \frac{\overline{LC}}{\text{Labor Allocation}} = \frac{\overline{LC}}{70\%} \quad (D-4)$$

\overline{TDMC} : Average Total Direct Manufacturing Cost for program

Using \overline{TDMC} , we can use the MC and OC allocations set previously to calculate the average Material (\overline{MC}) and Other (\overline{OC}) costs:

$$\overline{MC} = \overline{TDMC} * \text{Material Allocation} = \overline{TDMC} * 20\% \quad (D-5)$$

\overline{MC} : Average material cost for program

$$\overline{OC} = \overline{TDMC} * Other Allocation = \overline{TDMC} * 10\% \quad (D-6)$$

\overline{OC} : Average other costs for program

Here we assume the \overline{MC} and \overline{OC} costs will remain constant throughout the program for the following reasons:

- **Material costs:** As production increases, an OEM would typically expect their suppliers to provide materials at a decreasing price. This incentivizes their suppliers to lean out their production process and allows the OEM to share in the savings. Typical learning rates associated with material suppliers is 95%. However to ensure a conservative estimate, the result is assumed to hold the \overline{MC} constant.
- **Other costs:** Similarly, OCs will also decrease over time at a learning rate of about 95%. Again for a conservative estimate the result is assumed to hold the \overline{OC} constant.

Since we assume MCs and OCs remain constant over the life of the program, we can calculate the total direct manufacturing cost for any ship set ($TDMC_n$) as follows:

$$TDMC_n = LC_n + \overline{MC} + \overline{OC} \quad (3-9)$$

D.2 Indirect Costs

Indirect costs are costs that cannot be attributed to making one particular product but are absorbed across many production lines and products. Resources that are pooled together under Overhead (OH) such as utilities, equipment, management labor, and tooling are common indirect manufacturing costs and from Ascent's experience normally sum to about 20% of DC's. While there are many ways to allocate OH, this investigation simply adds 20% of the \overline{TDMC} to each ship set to arrive at the total manufacturing cost for each ship set (TMC_n):

$$OH = \overline{TDMC} * 20\% \quad (D-7)$$

Thus,

$$TMC_n = TDMC_n + OH \quad (3-10)$$

Appendix E – Equations: Establishing Standard Manual and Automated Cycle Times

E.1 Establishing Standard Manual Cycle Times

Each assembly step within a PPD is designated a Work Instruction (WI). An assembly WI specifies the assembly instructions, number and type of fasteners to be installed, and the associated installation time. As seen in section 2.2, the general labor steps associated with manually installing fasteners are:

1. Set up assembly tooling
2. Temporarily fasten fuselage skin
3. Drilling and countersinking
4. Disassemble & de-burr holes
5. Reassemble and install fasteners

Using the results of the Reach Study, each WI_i that will now be automated is added to the SoA and the labor hours are summed. Table 3 portrays a fictitious example:

Table 3: Work Instruction fastener installation example

| Work Instruction | Current Manual Process | Hours |
|------------------|--|------------|
| XX-XXX-X-XXXX | DRILL FRAMES COMMON TO SHEAR TIES | 1.8 |
| XX-XXX-X-XXXX | DISASSEMBLE AND DEBURR | 1.3 |
| XX-XXX-X-XXXX | INSTALLL FASTENERS | 1 |
| | Manual Assembly Time (MAT_i) | 4.1 |

The above example demonstrates that this specific i^{th} fastener installation WI requires 4.1 hours of manual assembly time (MAT). The SoA_{100} for T100 of an automation project is the sum of all MAT for all WIs within each assembly category (AX) that will now involve automation, see Equation (E-1).

$$SoA_{100} = \sum_{AX} \sum_{i=1}^I MAT_i \quad (E-1)$$

i : Work Instruction number

I : Total number of WIs that are within the Scope of Automation

AX : Assembly category

MAT_i : Manual Assembly Time for the i^{th} Work Instruction

E.2 Establishing Standard Automation Cycle Times

In an attempt to not overly complicate the process, the author recommends maintaining a macro view of the automation assembly process to establish a standard automation cycle time. While distinctive material stack ups will drive different drilling times coded into the CNC program for each fastener, this level of detail is unnecessary at this stage. This section uses a technique developed by Matt Dunaj at Ascent Aerospace to estimate a standard automation cycle time. Figure 20 shows an example of an automation cycle time and reveals that drilling time is not on the automation cycle time critical path. The following sections describe a technique for determining an automated fastener installation cycle time in adequate detail. After pre-drilling preparation, there are generally three cycle time situations for automated drilling and fastener installation:

- Send nominal fastener, use nominal fastener
 - The preprogrammed nominal fastener is sent to end effector and installed
- Send nominal fastener, use grip change
 - The preprogrammed fastener is sent but is ejected from end effector because it shall not be installed. Consequently, another fastener is sent and installed
- Send measured fastener

- End effector measures material stuck-up thickness before feeder system sends the correct fastener to end effector and installs

Each situation is discussed below together with Figure 20 as a representative example of a shear tie to frame cycle time study.

Example: Shear tie to frame

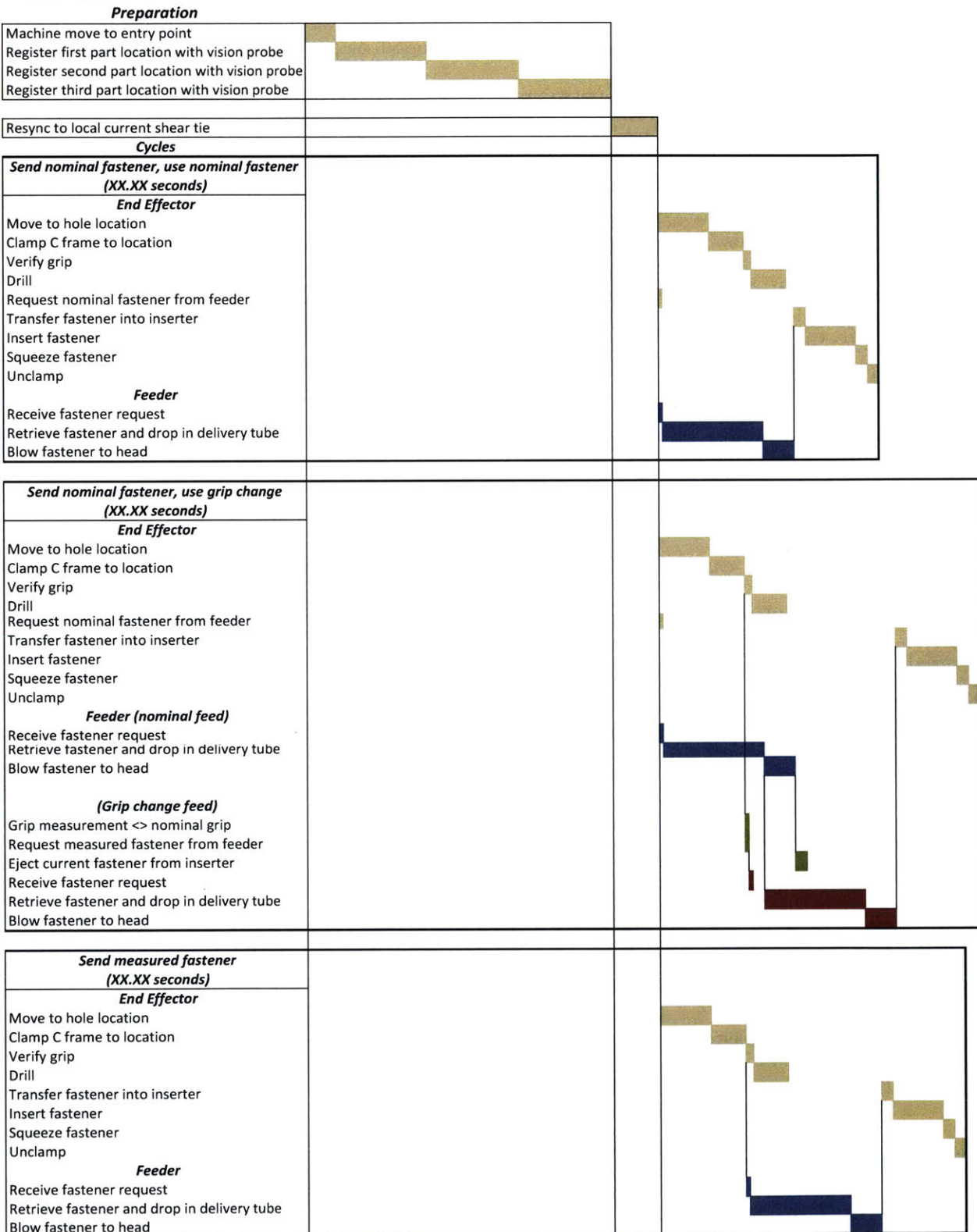


Figure 20: Standard automation cycle time study example

E.2.1 Preparation

No matter the fastener type, automation requires a period of preparation using machine vision metrology to account for geometric positioning errors from tolerance stack-ups and alignment issues from the manual placement and tacking of parts. A common machine vision metrology system will use three vision targets to triangulate the drill head's position and perpendicularity to the material surface. This ensures the holes drilled by automation are acceptable to the quality required for assembly. Metrology positioning is most critical when the drill head moves from one hole pattern to the next. However, as a conservative first approximation, one should assume the preparation step is required for every fastener. The occurrence of metrology positioning is reduced over time through optimization activities.

E.2.2 Send nominal fastener, use nominal fastener

This represents the best-case cycle time situation. A pre-programmed fastener is requested from the feeder system while the end effector is locating the hole through metrology. Here the measured material stack thickness is found to be within the acceptable limits of the given fastener's technical data sheet, therefore once the end effector completes drilling, it receives the nominal fastener and installs it immediately.

E.2.3 Send nominal fastener, use grip change

Here the measured material thickness is not within the acceptable limits of the pre-programmed nominal fastener's technical data sheet. Therefore, a request is made to the feeder to send another fastener with the correct grip length, even if the end effector has not yet received the nominal fastener. The nominal fastener is ejected and the new fastener with the correct grip length is installed. If a grip change occurs it adds 1.5 – 5.5 seconds to the best-case cycle time.

E.2.4 Sending a measured fastener

This is the most conservative technique where the request for a fastener is postponed until the end effector verifies the material thickness. Thus, if there is a discrepancy a fastener is not wasted and

the correct fastener does not need to wait for the incorrect fastener to clear the feeder blow tube. However, the measured fastener option typically adds 1-2 seconds to the best-case cycle time.

Appendix F – Equations: Labor Savings

This section describes a standard process of quantifying the labor savings due to automation relative to a manual assembly line. Thereafter, in section 3.2.1.6 a prediction model is developed that uses historical data to predict the labor savings with only the data available from an OEM's Request for Interest (RFI).

F.1 Calculating Labor Hour Savings

With automation installed, the new automated assembly process consists of two parts: 1) manual tacking (TT) and 2) automation assembly time (AT). Tacking time is estimated in Equation (F-1) as the equivalent proportion of manual process time associated with the remaining manually tacked fasteners.

$$TT_{100} = \sum_{AX} (1 - \kappa_{AX}) * SoA_{100_{AX}} \quad (F-1)$$

TT_{100} : Manual taking time for T100

$SoA_{100_{AX}}$: Scope of Automation at T100 within an assembly category AX

The automation labor time is shown in Equation (F-2) simply as the number of automated fasteners multiplied by the standard automation cycle time (ACT) established in section 3.1.4.3.

$$AT_{100} = \sum_{AX} \alpha_{AX} * ACT \quad (F-2)$$

AT_{100} : Automation assembly time for T100

ACT : Standard Automation Cycle Time

Hence, the total assembly time for the new automated process is the sum of tacking and automation time, see Equation (F-3). While the labor savings is the difference between the total manual assembly time and the new automated assembly time, see Equation (F-4).

$$TAAT_{100} = TT_{100} + AT_{100} \quad (F-3)$$

$TAAT_{100}$: Total automated assembly time for T100

$$LHS_{100} = SoA_{100} - TAAT_{100} \quad (F-4)$$

LHS_{100} : Labor Hour Savings for T100

Continuing the fastener installation WI_i example set in Appendix E where the MAT_i was estimated at 4.1 hours we can calculate the labor hours saved for that i^{th} WI :

$$\kappa_{AX,i} = \frac{\alpha_{AX,i}}{\gamma_{AX,i}} = \frac{135}{150} = 90\%$$

$$TT_i = (1 - \kappa_{AX,i}) * SoA_{AX,i} = (1 - 90\%) * 4.1hours = 0.4hours$$

Using an automated cycle time of 30 seconds:

$$AT_i = \alpha_{AX,i} * ACT = 135 * \frac{30seconds}{3600seconds} = 1.1hours$$

$$TAAT_i = TT_i + AT_i = 0.4hours + 1.1hours = 1.5hours$$

Finally:

$$LHS_i = MAT_i - TAAT_i = 4.1hours - 1.5hours = 2.6hours$$

Therefore, this fictitious fastener installation package example yields a labor saving for WI_i of 2.6 hours. If the PPDs are in fact set to estimate T100, the Total Labor Hour Savings for H_{100} ($TLHS_{100}$) are calculated by repeating this process and summing for all WIs that are within SoA_{100} . Note, since automation only influences WIs within the SoA, for all calculations moving forward we will only consider assembly hours within the SoA for each ship set n (SoA_n)

$TLHS_{100}$ represents the maximum potential hour savings available for this assembly line at ship set 100 (SS_{100}). However two factors work to vary its potential effect in practice with each respective ship set:

1. **Automation integration period:** The period where the OEM's technicians are debugging and learning to use the automation
2. **Manual assembly learning effects:** The efficiency improvement of the manual line due to learning if automation was not introduced to the line.

F.1.1 Automation Integration Period

If:

$$SS_n \leq (ISS + \mu) \quad (F-6)$$

ISS : ship set where automation is implemented

μ : Number of ship sets required to fully integrate automation

Then:

$$TLHS_n = MAX \left(TLHS_{100} * \frac{SS_n - ISS}{\mu}, 0 \right) \quad (F-7)$$

$TLHS_n$: Total labor hours saved for ship set n

Else:

$$TLHS_n = TLHS_{100} \quad (F-8)$$

F.1.2 Manual Assembly Learning Effects

As previously mentioned in section 3.1.4, the potential labor hour savings are set according to the PPDs for a specific ship set, typically SS₁₀₀. Yet, as the alternate scenario of a purely manual assembly process continues down its learning curve from SS₁₀₀, **TLHS_n** will not remain constant but decrease proportionally to the learning curve. On the other hand, if we back calculate up the learning curve to ISS, **TLHS_n** will instead increase at the same proportional rate. The proportional difference is re-introduced as the Efficiency Factor of Ship Set n (**EF_n**), from Equation (3-6):

$$EF_n = \frac{H_n}{H_{100}}$$

If we multiply **TLHS_n** with **EF_n** the Actual Labor Hours Saved (**ALHS_n**) from introducing automation at Ship Set n are revealed in Equation (3-13):

$$ALHS_n = TLHS_n * EF_n$$

ALHS_n = Actual labor hours saved due to automation for ship set n. This quantity accounts for the learning effects happening in the alternate scenario of a purely manual assembly process

F.2 Calculating Labor Dollar Savings

From here the labor savings for year Y are calculated by multiplying the total ALHS for year y by the OEM's blended labor rate for the same year. The general equation is given in Equation (3-14):

$$LS_y = \sum_{n \in y} ALHS_n * LR_y$$

LS_y = Monetary labor savings for all ship sets within a given year y

F.3 Calculating Labor Savings from OEM RFI Data

In this section we will use a combination of a suppliers historical data from past automation programs and a current OEM’s RFI to predict the labor hours saved due to automation. Keeping in mind we are assessing T100, the first task is to collect and sort historical data based on the assembly categories listed in Section 3.1.4:

- Longitudinal aircraft fuselage skin splice joint
- Circumferential aircraft fuselage skin splice joint
- Door Surround to aircraft fuselage skin fastening
- Shear tie to skin fastening
- Shear tie to aircraft airframe fastening

For each assembly category (AX), the percent automated (κ), and standard manual assembly time (MAT) according to the PPDs is documented and averaged. However, due to the number of fasteners in any one assembly program, the data from a single program can yield a surprisingly accurate prediction of the labor hours saved. Table 4 demonstrates a fictitious example of automation percentages for each assembly category while Table 5 provides an example of a standard manual cycle time for the ‘longitudinal fuselage skin splice’ category.

Table 4: Percent Automated per Assembly Category

| Assembly Category (AX) | Percent Automated (κ) |
|---|-----------------------------------|
| Fuselage Skin to Stringers (Single Contour) | 90% |
| Fuselage Skin to Stringers (Double Contour) | 90% |
| Longitudinal Fuselage Skin Splice | 92% |
| Circumferential Fuselage Skin Splice | 85% |
| Shear Tie to Frame | 75% |
| Shear Tie to Skin | 70% |
| Door Surround | 70% |

Table 5: Standard Manual Cycle Time per hole at T100

| Longitudinal Fuselage Skin Splice | Standard Time (seconds) |
|--|------------------------------------|
| Drill & Countersink | 85 |
| De-burr | 25 |
| Install Fastener | 80 |
| Total Manual Cycle Time (seconds) | 190 |

The next task involves establishing the standard automated cycle time (see Appendix E) depending on whether the automation process is drilling only, fastening only, or drilling and fastening. See Table 6 below for a fictitious example.

Table 6: Typical Automated Cycle Time per hole

| Automated Cycle Time Category | Seconds |
|--------------------------------------|----------------|
| Drill Only | 15 |
| Install Fastener Only | 20 |
| Drill and Install Fastener | 30 |

From here, the final data input is the fastener count from an OEM's RFI allocated amongst the different fastening categories. Table 7 depicts a fastener count example from an OEM's RFI.

Table 7: Fastener Count from OEM RFI

| Fastener Count (FX) | Rivets |
|--------------------------------------|---------------|
| Longitudinal Fuselage Skin Splice | 6,120 |
| Circumferential Fuselage Skin Splice | 8,070 |
| Shear Tie to Frame | 5,721 |
| Shear Tie to Skin | 2,569 |
| Door Surround | 3,560 |
| Total | 26,040 |

With the fastener count data from an OEM's RFI it is now possible to make an educated estimate of LHS_{100} that pertain just from the reduction in assembly cycle time from automation. The final steps to estimate the savings in labor hours using this model are as follows:

1. Evaluate the current SoA_{100} for each assembly category (AX) by summing each product of the standard manual cycle times against the fastener counts.

$$SoA_{100} = \sum_{AX} MCT_{AX} * FX_{AX} \quad (F-9)$$

MCT_{AX} : Standard manual cycle time for assembly category AX

FX_{AX} : Fastener count for assembly category AX

2. Estimate the $TAAT_{100}$ required to perform the same task by summing manual tacking and automation assembly in each assembly category.

$$TAAT_{100} = TT_{100} + AT_{100} = \sum_{AX} (1 - \kappa_{AX}) * SoA_{AX} + \sum_{AX} \alpha_{AX} * ACT \quad (F-10)$$

3. Find the labor hours saved by taking the difference between manual and automation hours.

$$LHS_{100} = SoA_{100} - TAAT_{100} \quad (F-11)$$

This model can be used to estimate the hours saved with automation for an OEM within minutes rather than days. The prediction made with this model will be checked during the RFQ stage of a program with the deep dive technique described in section 3.1.4.

Appendix G – Equations: Quality Savings

Savings that arise from increased quality are two fold: 1) less rework labor hours and 2) less material scrap.

1. Rework savings (ρ_y) per year y as a result of eliminating rework can be calculated as follows:

$$\rho_y = \sum_{n \in y} LC_n * (\overline{SRR}) * 2 * RRedR * RS \quad (G-1)$$

\overline{SRR} : Average scrap and rework rate

$RRedR$: Rework and scrap reduction rate: since rework and scrap are not fully eliminated.

RS : Rework Scope: Scrap and rework is only reduced from tasks that are performed by automation:

$$RS = \frac{SoA_{100}}{H_{100}} \quad (G-2)$$

Note: a factor of two is applied to account for the assumption that rework hours take twice as long to accomplish relative to installation since rework hours includes time spent both removing and reinstalling a fastener

2. Scrap saved (σ_y) per year y as a result of eliminating scrap can be estimated as follows:

$$\sigma_y = \sum_{n \in y} \overline{MC} * (\overline{SRR}) * RRedR * RS * \quad (G-3)$$

Finally, the total quality savings (TQS_y) per year y from automation is the sum of rework and scrap savings.

$$TQS_y = \rho_y + \sigma_y \tag{G-4}$$

Appendix H – Equations: Health & Safety Savings

Annual savings from increased health & safety ($H\&SS_y$) for year y is calculated as follows:

$$H\&SS_y = \sum_{n \in y} SoA_n * IR * \bar{IC} * IRedR \quad (H-1)$$

Where,

$$SoA_n = SoA_{100} * EF_n \quad (H-2)$$

$H\&SS_y$: Annual health & safety savings

IR : Injury rate: number of injuries per million labor hours

\bar{IC} : Average injury cost

$IRedR$: Injury reduction rate: since injuries are not fully eliminated

Appendix I – Equations: Rate Tool Savings

The five general steps to estimate the level of rate tooling required for a given year is as follows:

1. Determine required production hours per assembly station at T100:

The first step requires determining the production hours ($\mathbf{\Pi}_S$) required for each assembly station (S) at T100 based on an OEM's PPDs.

2. Allocate initial tooling amongst assembly stations based on production hours:

For the first year of production the cost of tooling for each assembly station ($T_{S,1}$) is found by allocating the initial tooling investment (ITI) based on the production hours required at each station. The tooling allocation burden rate is the ratio of $\mathbf{\Pi}_S$ to the total production hours of SS₁₀₀ (H_{100}), see Equation (I-1):

$$T_{S,1} = \frac{\mathbf{\Pi}_S}{H_{100}} * ITI \quad (I-1)$$

3. Estimate required headcount per station:

The limiting factor of an assembly station is how many mechanics can an assembly station hold while still allowing them to work effectively. Consequently, the required headcount in a certain assembly station is what could drive further investments in tooling.

As production continues after the initial year of production, annual production quantities will vary according to the OEM's production schedule. Calculating the required headcount for a particular station in a given year to achieve the production schedule throughput is challenging for two reasons: 1) production schedule changes every year, and 2) each ship set is produced with a different cycle time since production is continuing down the learning curve. First, to find the production hours required at a station for a given year y ($\theta_{S,y}$) we multiply $\mathbf{\Pi}_S$ by the average Efficiency Factor for a given year y (*Avg. EF_y*)

$$\theta_{s,y} = \Pi_s \cdot Avg.EF_y \quad (I-2)$$

From here, the next step is to calculate the required headcount ($HX_{s,y}$) of each station for a given year with respect to the required production rate and available monthly production hours per employee.

$$HX_{s,y} = \frac{[\theta_{s,y} \cdot RR_y]}{\omega} \quad (I-3)$$

$HX_{s,y}$: Required headcount of mechanics at a given station s in a given year y

ω : Available monthly production hours per employee

RR_y : is the required monthly production rate in year y, see Equation (I-4).

$$RR_y = \frac{PQ_y}{12 \text{ months}} \quad (I-4)$$

PQ_y : Production quantity, the number of ship sets produced in year y with respect to the production schedule

4. Calculate increase in tooling required to keep headcount within maximum limits of a given station:

Continuing on, we specify the maximum headcount ($MaxH_s$) for each assembly station based on the workflow and physical spatial constraints of an assembly station. Typical maximum headcounts for any one station is eight to 10 mechanics. If during a production year the headcount at a station exceeds the maximum allowed, increase the level of tooling ($TF_{s,y}$) at said station to bring headcount to within the acceptable limit. The mathematical representation is given in (I-5) through (I-7).

For every station and every production year, if:

$$HX_{S,y} > MaxHX_S \quad (I-5)$$

Then:

$$TF_{S,y} = TF_{S,y} + 1 \quad (I-6)$$

$TF_{S,y}$: Tooling factor that scales the tooling investment at a given station in a given year

Else:

$$TF_{S,y} = TF_{S,y} \quad (I-7)$$

Thus, the required tooling investment at a station for a given year is found by multiplying the initial tooling investment by the tooling factor:

$$T_{S,y} = T_{S,1} * TF_{S,y} \quad (I-8)$$

The total tooling required per year (T_y) is simply the sum across all stations:

$$T_y = \sum_{S=1}^z T_{S,y} \quad (I-9)$$

z : Total number of assembly stations

5. Once installed, tooling cannot be returned to vendor if it is no longer required

Finally, since tooling is customized to a specific product and set of PPDs the tooling cannot be sold or returned to the supplier if production ramps down. The level of tooling installed each year is given below.

Level of tooling installed (***TInst_y***) for a given year *y* is given by:

$$\mathbf{TInst}_y = \mathbf{MAX}(T_y, T_{y-1}) \quad (\text{I-10})$$

Level of tooling increase (***TIncr_y***) required for a given year *y* is given by:

$$\mathbf{TIncr}_y = \mathbf{MAX}(T_y - T_{y-1}, 0) \quad (\text{I-11})$$

Appendix J – Equations: Automation Downtime Risk

Calculating the cost attributed to unforeseen automation downtime for a given year requires three general steps:

1. Calculate Actual Production Hours (APH) by multiplying the available production hours per year by a productivity rate:

$$APH = \phi * \varepsilon \quad (J-1)$$

ϕ : Annual available production hours per year

ε : Average production productivity rate

APH: Actual production hours that are available each year. APH is the sum of both annual uptime and annual downtime hours of the automation assembly line, see Figure 21:

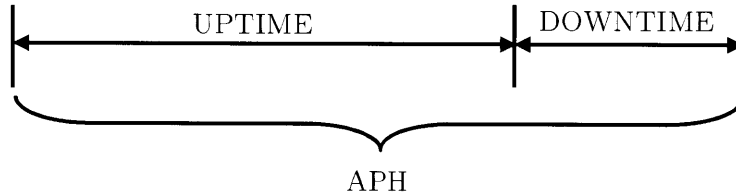


Figure 21: Actual production hours is the sum of uptime and downtime

2. Determine how much revenue is accrued on an hourly basis, introduced here as the Revenue Accrual Rate (RAR_y). Equations (J-2) through (J-4) demonstrate how it is calculated for a given year by dividing the collective annual revenue of the assembly line by the annual uptime of the automation.

$$RAR_y = \frac{Rev_n * PQ_y}{Uptime} \quad (J-2)$$

RAR_y: Revenue accrual rate for a given year.

Where:

$$Uptime = APH - Downtime \quad (J-3)$$

and:

$$Downtime = APH * \eta \quad (J-4)$$

η : Failure rate (%)

3. Finally, the annual Automation Downtime Cost (***ADC_y***) is found by multiplying ***RAR_y*** by the tolerated number of annual downtime hours.

$$ADC_y = RAR_y * Downtime \quad (J-5)$$

ADC_y: Automation Downtime Cost for a given year y