Determining Appropriate Levels of Robotic Automation in Commercial Aircraft Nacelle Assembly

by
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B.S. Aerospace Engineering, Pennsylvania State University, 2005

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

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Abstract

This thesis examines the application of reconfigurable industrial robotics in the assembly of the engine nacelle inlet for a commercial aircraft. In addition to addressing the achievable level of automation, this thesis also reviews the evaluation of robotics vendor proposals and the accompanying financial justification requisite for implementation.

The aircraft industry has long been dominated by manual fabrication and assembly methods. Variability in human skill, however, results in defects, rework, and reduced production throughput. One approach to reduce variability, decrease cycle time, and increase throughput is the implementation of robotic automation for various assembly tasks.

Low aircraft production volumes have made it difficult to justify large investments in robotic automation. Decreasing cost and increasing capability of industrial robotics, however, are making investment more palatable. The excellent repeatability of robotic automation can significantly reduce individual task times for a wide range of operations. Standard automated task times are 60–85% lower than standard manual task times for drill and fasten operations which represent the greatest opportunity for cycle time improvements because typical aircraft assembly requires tens of thousands of holes and fasteners.

The optimal level of automation is a balance among decreasing manual touch time, improving production capacity, and increasing automation costs. A semi-automated solution is shown to reduce manual touch time by 70% and total touch time by 30%. The implementation of this solution requires an investment of tens of millions of dollars and results in present value savings of hundreds of millions of dollars for the program lifetime.

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Chapter 1

Introduction

The aircraft industry has a long tradition of manual fabrication and assembly. Variability in human skill, capability, and repeatability have led to exhaustive inspection practices, an expectation of defects, and the need for rework[*]. This variability results in aircraft that are in some ways unique from all other aircraft produced—even of the same model and from the same assembly line. In turn, the expectation of rework reinforces the acceptance of variability. The time and labor required to address defects and mitigate variability cost money and negatively impact production cost, capacity, and cycle time.

The long tradition of manual aircraft production is closely related to low production volumes[†]. Automated machinery, especially robotics, have been widely adopted in the automotive, semiconductor, and electronics industries where high volumes necessitate low variability to maintain capacity and throughput. Flexible, or reconfigurable, industrial robotics systems provide common motion platforms for customizable tools, or end effectors. The commonality of the platform provides reliable human and machine interfaces, known levels of accuracy, and lower costs. Despite widespread adoption in other industries, the high unit value of aircraft, the low production volumes, and the high complexity of aircraft systems—coupled with the historically high cost of automated systems—have stifled efforts to modernize aircraft manufacturing.

Even with economic uncertainty in the short term and increasing fuel and ticket costs in the long term, the number of passengers traveling by commercial aircraft is expected to double by the year 2035 [10]. The worldwide fleet of commercial aircraft is projected to grow significantly to satisfy this increase in demand. The growth of the commercial aircraft fleet necessitates unprecedented production rates that promise to strain current capabilities.

The worldwide commercial airplane market is dominated by Airbus and Boeing. Figure 1.1 shows their orders and deliveries over the period 1989–2013 [1, 8]. Airbus deliveries

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[*] Private communications with aerospace managers, employees, and technicians across the industry.

[†] Ibid.

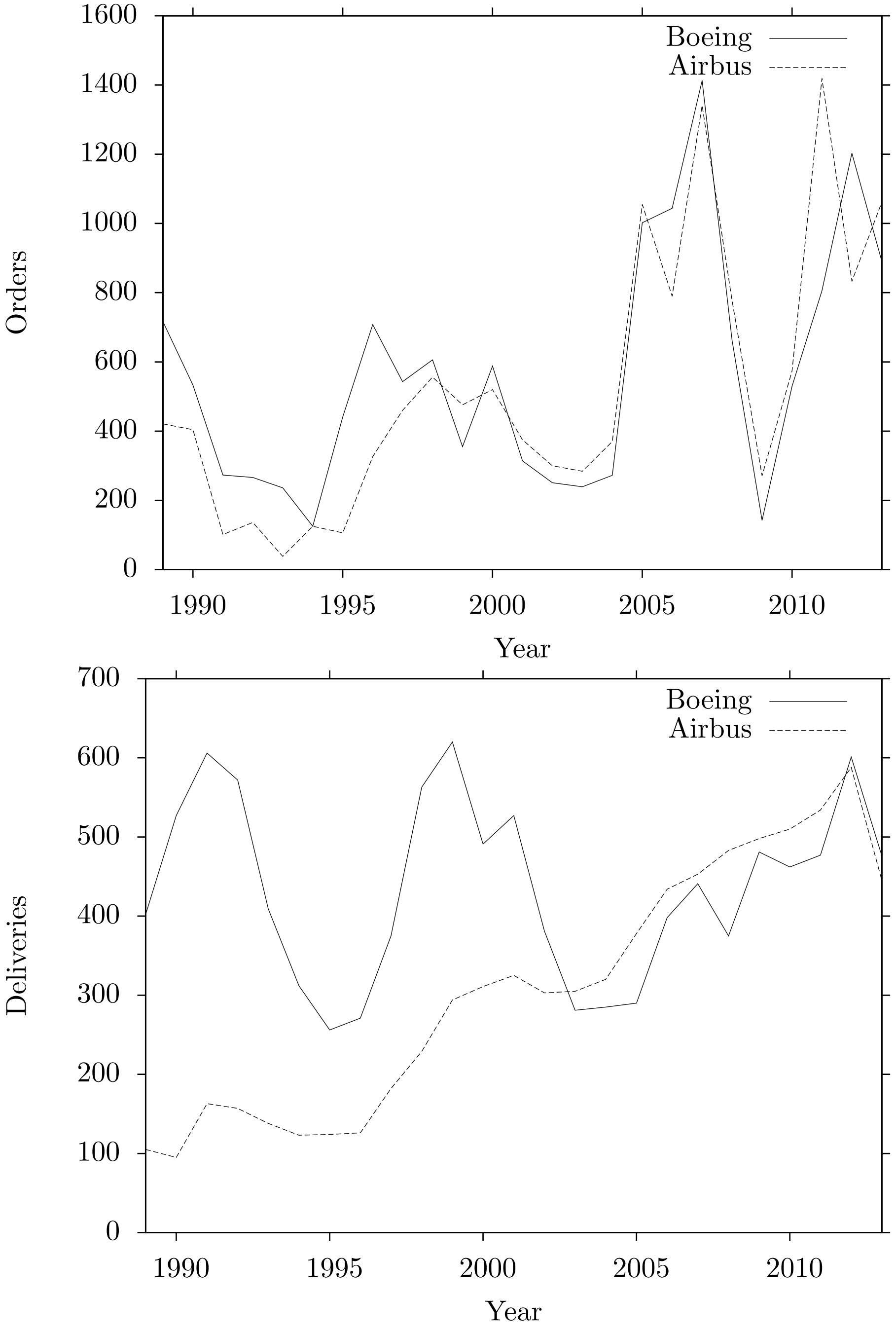


Figure 1.1: Commercial airplane market share

have risen steadily over this period while orders have kept pace with Boeing. The result has been the erosion of Boeing's share as Airbus has captured approximately half of the market. This near-duopoly is increasingly threatened, however, by new market entrants such as Bombardier, Comac, and Embraer. These entering players are putting downward pressure on aircraft pricing and the incumbents are scrambling to cut production costs to remain competitive[‡]. Price flexibility is facilitated by reduced recurring costs which become a strategic differentiator, especially in consideration of the importance of price for airlines that operate on thin margins.

The combination of increasing production volumes and the need to decrease cost has renewed attention on reconfigurable robotic solutions in commercial aerospace. Non-robotic, non-reconfigurable automated solutions have been implemented in aircraft assembly for many years with varying levels of success. The custom nature of non-reconfigurable systems has resulted in high cost and low flexibility. The widespread adoption of reconfigurable robotics in other industries, however, has resulted in the commoditization and standardization of these robotics systems and capabilities.

1.1 Problem Statement

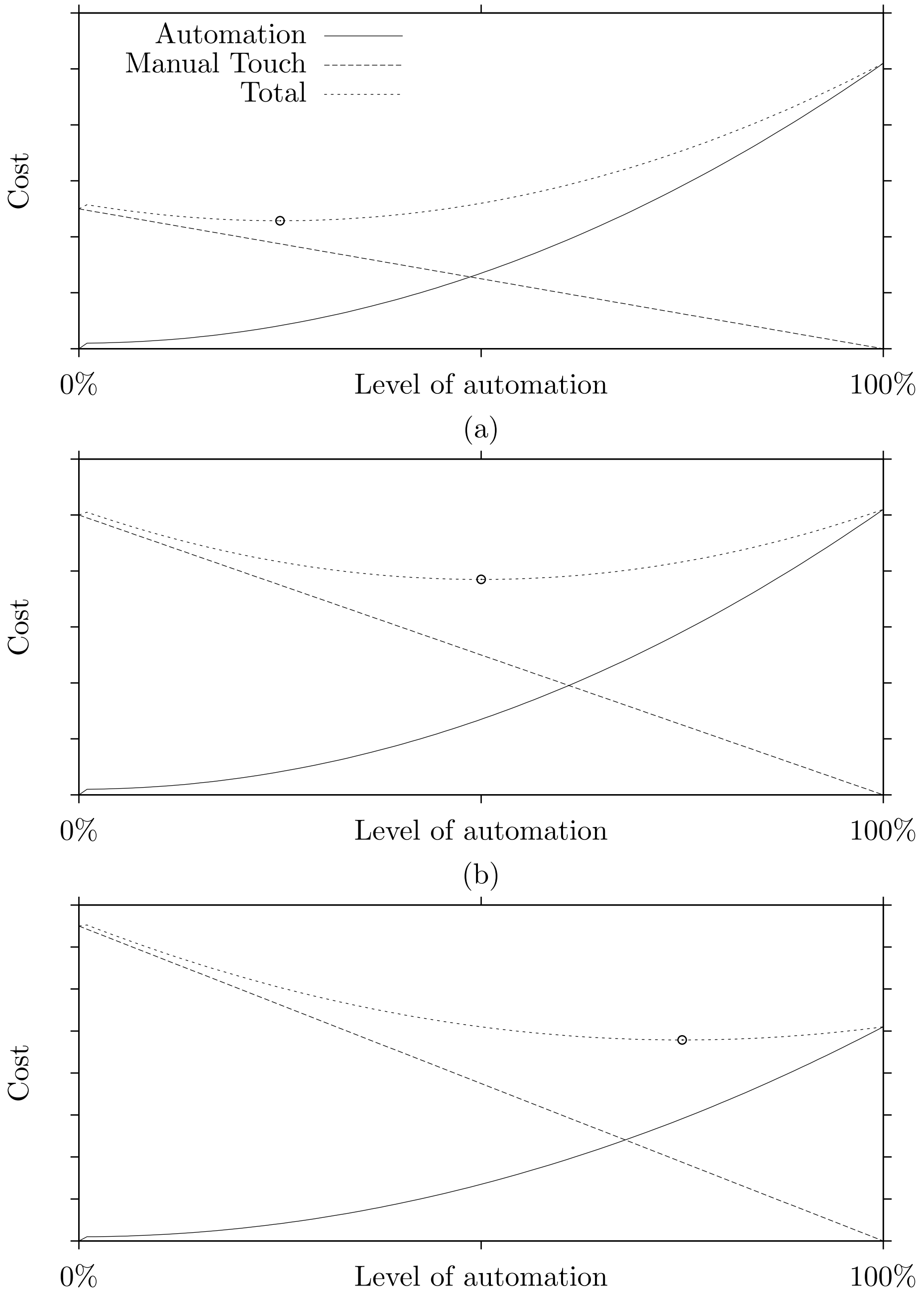
As robotics are increasingly adopted in commercial aircraft assembly, it has become clear that manufacturing strategy is often not aligned with automation implementation decisions [18]. Specifically, the level of automation is often of an ad-hoc nature. Robots may be purchased, for example, and later idled because of lack of commitment to work through implementation challenges. Operators and technicians may view robotics unfavorably and as a threat to job security. Automation may be implemented for the sake of adopting novel technology without consideration for the cost-effective balance between manual and automated operations.

The aim of this thesis is to examine the relationship between the achievable level of automation and the total production cost of the engine nacelle inlet[§] for a commercial aircraft. In practice, this is complicated by the necessity to work with third-party robotics vendors and the accompanying complexities of supplier management. While this thesis focuses on an analysis of this particular application, it is believed that the resultant insights are generally applicable to all areas of commercial aircraft assembly. The achievable level of automation and its attending cost is influenced by the degree to which the system is designed for automation and by the subsequent choice of systems integrator.

Figure 1.2 shows notional cost scenarios for varying levels of automation. The level of automation may be characterized by the linear decrease in manual labor, or touch time.

[‡] Ibid.

[§] The nacelle is an aerodynamic covering of the engine. In addition to reducing drag, it may also facilitate the routing of electrical, hydraulic, pneumatic, or fuel systems. The nacelle inlet is the forwardmost part of the nacelle and generally comprises the leading edge and internal structure back to the engine fan. The inlet diffuses and slows incoming air as it enters the engine.



(a)

(b)

(c)

Figure 1.2: Levels of automation

The cost of automation, then, increases superlinearly with the level of automation while manual touch time decreases linearly [12]. There is a point at which the increasing cost of automation and the decreasing cost of labor yield minimum total cost. Figure 1.2 shows representative low, medium, and high optimal levels of automation in subfigures (a), (b), and (c), respectively, with the minimum total cost depicted by a small circle. Any reduction in total cost is desirable and a range of automation levels may satisfy this requirement.

Although the ultimate goal is to identify the optimum level of automation—the minimum total cost—there is no parametric equation that reveals all the costs of implementation for a particular level. This may result in a decision that reduces total cost without minimizing it. Each point that defines the curve may represent an entire project or a proposal from a vendor. Any significant change to the statement of work for an automated system necessitates a new study. Furthermore, cost likely varies among aircraft programs and competitors. There is, however, much data regarding the cost of labor. Even so, this provides half the necessary data to determine optimal levels of automation.

1.2 Methodology

Research for this thesis was conducted onsite as a member of the team responsible for the design and production of a commercial aircraft engine nacelle inlet in what will become one of the largest implementations of robotic automation in the aircraft industry. Unlike many efforts that introduce automation to improve efficiency and throughput on existing assembly lines, this initiative offers the opportunity to start a new production line in a greenfield factory.

Much of the content for this document was gathered from in-depth reviews of the inlet design and from analysis of the production plan. Direct observation of the challenges and shortcomings of existing non-robotic automated technologies provided a reference point against which more flexible, robotic technologies could be assessed. This was supplemented by visits to robotics vendors, robotics research laboratories, and robotic assembly lines in order to better understand the current and future state of automated technologies. Collaboration with others researching robotic automation in aircraft assembly provided insight into differing needs and viewpoints.

Additional content was derived from meetings and discussions with supplier management and finance. A decision matrix was employed to score the relative technical merit of several vendor proposals and financial tools were utilized to justify capital investment. Specific recommendations are made and general implications are discussed.

1.3 Thesis Overview

Much of the existing literature addressing this topic takes one of two approaches. The first approach focuses narrowly on particular technologies or assembly operations without addressing some of the larger organizational issues [23, 33]. Organizational issues are an important element in the implementation and adoption of robotic automation because structure, politics, and culture impact the decision-making process. Investments in new technologies must be justified and technical or operational risks must be mitigated. The other approach broadly addresses the adoption of automation from a strategic or business perspective without exploring the details of implementation [18, 24, 30]. Some research has addressed both high-level management considerations as well as lower-level technical issues but much of this is outdated and reflects old automation capabilities, efficiencies, and costs [20].

This thesis attempts to address strategic, business level objectives as well as practical implementation considerations for modern, reconfigurable industrial robotics. This is accomplished through the lens of the automated assembly of the engine nacelle inlet for a commercial aircraft. Certain concepts are purposely simplified and some details omitted in an effort to provide broad understanding that favors clarity over exhaustive detail. Beyond this introduction, the remaining chapters build one upon the other to describe the historical and industry context, explain common production methods, explore the benefits of automation, and examine real world considerations for implementing robotics in aircraft assembly.

Chapter 2 describes traditional aircraft fabrication and assembly methods including material selection, metal and non-metal forming, drilling, fastening, sealing, inspecting, and moving of parts. This provides context for challenges faced in applying automation to aircraft assembly.

Chapter 3 discusses the benefits of automated assembly. This includes reduced individual task times and lower cumulative touch times with improved repeatability that leads to fewer defects. Task times are reduced by approximately 75% and touch times by approximately 30%. Robotic and non-robotic automation techniques are examined and a case is made for flexible robotics in favor of large, stationary equipment also known as monuments.

Chapter 4 examines the planning and implementation of a robotic, semi-automated assembly line for the engine nacelle inlet of a commercial aircraft. It covers assembly and build plan considerations for automation, technical evaluation of supplier proposals, and financial justification. The implementation of a semi-automated assembly line offers a present value savings of $250M.

Chapter 5 summarizes the findings of this thesis, identifies general implications, and proposes future areas of research. Much work can be done to identify the optimal balance of manual and automated assembly operations.

Chapter 2

Aircraft Fabrication and Assembly

A discussion of robotic automation in commercial aircraft assembly would be incomplete without first addressing the materials and methods used to fabricate and assemble those aircraft. This chapter aims to familiarize the reader with some of the more common materials, fabrication approaches, assembly methods, and hardware employed in the production of commercial aircraft. This content is not comprehensive nor exhaustive—nor does it aim to be. The concepts outlined herein represent a core sample of knowledge gleaned from engineering design reviews, build plan reviews, document reviews, observation, and discussion with maintenance technicians in the factory*. Familiarity with materials and methods provides a foundation upon which automated assembly can be addressed; without this knowledge, the challenges of implementing robotic automation cannot be fully appreciated. These topics are relevant to robotic automation for at least two reasons. First, industry regulations and manufacturing best practices are well established and unlikely to radically shift in the near term. This means efforts to implement robotic automation must begin with the status quo as a baseline. Second, the transition to an automated assembly approach naturally begins with well-understood manual methods. Material selection, in particular, is important in later sections that describe the build and assembly plan for an engine nacelle inlet.

This chapter begins with a discussion of the characteristics of some of the more common materials used in the manufacture of aircraft. These are broadly categorized as ferrous, non-ferrous, and non-metallic. Next, several methods of material fabrication are addressed. These include the rolling, forging, casting, and extruding of metals as well as the layup and curing of composites. Finally, various methods of assembly are explored. These tasks include drilling, filling, sealing, inspecting, and material handling.

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*This content is supplemented by information from the Aviation Maintenance Technician Handbook [9].

Material	Percent (%)
Aluminum	75
Carbon Fiber	10
Steel	9
Titanium	5
Miscellaneous	1
Total	100

Table 2.1: Material breakdown for traditional commercial aircraft

2.1 Material Selection

Many different materials are used in aircraft construction to satisfy the wide-ranging needs for strength, durability, hardness, conductivity, ease of fabrication, or other desirable characteristics that satisfy airworthiness and certification requirements. Most commercial aircraft are constructed primarily of aluminum alloys and composites with specific components made from titanium, steel, various alloys, and other non-metallic materials. The exact ratios of the various materials are specific to the manufacturer and model. Table 2.1 lists the approximate percentages of various materials used in traditional (non-composite) commercial aircraft [4]. Although composites are shown as comprising a small percentage of aircraft materials, they are increasingly replacing aluminum in aircraft structures for newer aircraft models. The primary structure of the Boeing 787 Dreamliner, for example, is comprised of 50% composites by mass [7].

Aircraft materials can be grouped broadly into three categories: ferrous metals, non-ferrous metals, and non-metallic materials. Materials for aircraft components are chosen to meet physical requirements and exhibit desired characteristics while minimizing weight and aircraft lifecycle costs (cost of raw material, cost of manufacture, cost of maintenance and repair). The designer may select materials with sufficient—rather than maximum—strength, for example, in order to take advantage of savings in other areas such as weight or cost.

2.1.1 Ferrous Metals

Metals that contain iron (Fe) are known as ferrous metals, the most common of which is steel. Steel is composed of iron, small amounts of carbon (0.05–2.0% by mass), and traces of various other elements. Steel can then be combined with other metals to create steel alloys. Iron and steel alloys generally have much more desirable material properties than pure iron. Steel, for example, may be up to 1000 times stronger than pure iron. Although steel is not used for primary structure in modern aircraft, alloyed steels are used for specific components and applications where its excellent strength characteristics are required. Examples include hardware such as wires, nuts, bushings, bearings, springs, bolts, and pins. Steel is also used in some structural members such as engine mounts, landing gear, and flap actuating components.

One of the more common steel alloys used in aircraft is corrosion-resistant steel (CRES), also known as stainless steel. As its name implies, CRES is especially useful in areas where corrosion is a concern. It is commonly used in fasteners, engine inlet and exhaust manifolds, or other areas where high strength is necessary in the presence of high temperature, moisture, or other corrosive environments (see Section 2.3.2 for a discussion of sealants that protect against galvanic corrosion). There exist other iron alloys, such as Inconel or Monel[†], that exhibit properties similar to CRES.

2.1.2 Non-ferrous Metals

Non-ferrous metals include materials such as aluminum, titanium, nickel, copper, and magnesium, among many others.

Aluminum

Aluminum has several desirable material properties including low density, resistance to corrosion, high damage tolerance, and relative ease of fabrication. Aluminum melts at a relatively low temperature (660 °C), is nonmagnetic, and is an excellent conductor. Its mechanical properties can be altered and tailored to specific needs and applications by combining small amounts of other metals such as nickel, tin, and copper, or by applying metalworking processes known as hot or cold treatments. Pure aluminum has a relatively low tensile strength whereas aluminum alloys are used heavily in aircraft due to their much higher strength. The strength of pure aluminum can be increased two-fold by certain metalworking processes (see Section 2.2) and five-fold by heat treatment or by combining with other metals to form alloys. Aluminum alloys also often demonstrate lower corrosion resistance than pure aluminum.

Titanium

Titanium has one of the highest specific strengths of any metal on earth. It is both stronger and denser than aluminum but less so than corrosion-resistant steel (CRES). Titanium has a very high melting point (approx. 1668 °C). Although its performance suffers after prolonged exposure to high temperatures, its ability to withstand low- and medium-duration high-temperature events make it essential for firewall and engine applications. Titanium has better fatigue and damage tolerance properties than aluminum or steel. Titanium exhibits excellent corrosion resistance that is superior to stainless steel (CRES).

[†] Inconel and Monel, both of which are typically much more expensive to acquire and manipulate than CRES, are used for high strength in extreme temperature and in high corrosion environments, respectively.

2.1.3 Non-metallic Materials

Various non-metallic and synthetic materials are used in the production of modern commercial aircraft. Examples include rubber (hoses, gaskets, and seals), ceramics, plastics (clips, windows, and interiors), and composites.

Composite materials used in aircraft manufacturing generally refer to the combination of high-strength, high-modulus fibers with epoxy or thermoplastic [20]. One common composite material in aircraft construction is carbon fiber reinforced plastic or polymer (CFRP), also known as carbon fiber matrix (CFM). As its name implies, carbon fibers reinforce an epoxy or plastic resin that hardens or cures and performs a function similar to that of an adhesive. This concept is similar in nature to concrete reinforced with rebar. Composite fibers may be braided into yarn, tape, or fabric prior to the application of resin. Each ply can be laid at a different angle. Typical angles include 0°, ±30°, ±45°, ±60°, and 90°. The sequence of angles in the multi-layer material determines the characteristics and properties of the resulting composite. Composites can be designed to carry tensile, shear, or torsion loads in specific directions. Composite materials have very high specific strength, extreme corrosion resistance, and long life. They can have tensile strength four to six times higher than aluminum or steel and demonstrate infinite fatigue resistance characteristics [3, 20]. Although composites are relatively expensive to fabricate, the increasing adoption and implementation of composite materials promises to make them more economical in the future [3].

Despite the many benefits of composite materials, there are undesirable characteristics as well. Composites generally have low inter-laminar strength that makes them susceptible to separation or delamination under certain loading conditions, particularly compressive loads. Composites are designed to carry directional loads and are much weaker in off-design loading conditions.

2.2 Fabrication Methods

Various methods and processes are used to manipulate raw materials into the shape and form desired prior to assembly. The method of fabrication and the temperature of the material impact the properties of the processed material. The manipulation of metal can change the grain structure and result in desirable increases in strength or hardness, for example. Processes such as stamping, rolling, forging, casting, and extruding are commonly used in the formation of metallic components for aircraft. Both metallic and non-metallic components can be machined to some degree.

Rolling The process of flattening or shaping solid metal into sheets (and some shapes) by feeding the metal between rollers. The distance between the rollers is less than the original thickness of the material and results in elongation as the material thickness decreases.

Many variations of rolling exist and their use is dependent on the desired outcome. A very common material formed by rolling is sheet metal.

Forging The process of shaping or plastically deforming solid metal by the rapid application of force, usually by pressing. Metals can be forged at cold, warm, or hot temperatures. Forging realigns the grain structure of the metal, the extent and final impact of which is determined in part by the temperature. Metals forged in cooler temperatures retain the altered grain structure while those forged in warmer temperatures experience some stress relief while the grain structure partially or completely realigns. Traditionally, metals were shaped and wrought by hand using a hammer and anvil. That process has largely been replaced by forging presses that subject the raw material to extreme pressures and force the metal into a die. This results in one piece of metal that takes the shape of the die. Forging presses produce consistent parts without wasting material.

Casting The process of pouring molten metal into a mold or forcing it into a die. The metal is allowed to cool and solidify afterwhich it is removed. Die casting generally results in greater precision metal parts than mold casting. Castings of both types normally yield lower strength than forged pieces of the same material because the metal is molten, plastic deformation does not occur, and the grain structure does not change.

Extruding The process of forcing solid metal through an opening in a die. The resulting piece is usually much longer than it is wide or high and has a cross section in the shape of the die. Extrusion is used to make channels, tubes, angles, T-sections, and Z-sections. Some metals may be extruded cold, but most metals are heated prior to extrusion.

Composite Fabrication The process of applying a reinforcement (such as yarn, tape, or fabric made of carbon or synthetic fiber) on a mold or tool between layers of epoxy or resin. Modern methods mostly use materials that are pre-impregnated with resin. The resin holds each ply in place relative to the one beneath it and a vacuum bag may be applied to ensure that the layer is pressed firmly against those beneath it. After all layers have been applied, the part is most often cured in an autoclave where it is subjected to high temperature and high pressure for an extended period of time. Curing causes the resin matrix to melt, flow, and harden. Curing yields a material that has characteristics not inherent in its constituent parts independently. After leaving the autoclave, the part must be trimmed to final dimensions before installation or assembly [3, 20].

Machining A subtractive process whereby a cutting tool removes material from the part of interest. Machining is usually performed with high accuracy equipment and is used where tight tolerances are required. Metal parts initially fabricated by rolling, forging, casting, and extruding can all be machined. Composite materials can also be machined. This can be especially useful since the nature of composite layup leads to inherent variation even within a single part.

Other Additional forms of material fabrication include stamping, hydro-forming, and superplastic forming. Stamping is a process used for sheet metal that is similar to forging or pressing. Hydro-forming uses water pressure to force sheet or tube metal into a negative die. Superplastic forming uses air pressure to force thin metal sheets into a negative die. Various other metal-working processes exist for specific applications, the details of which are left to the reader to explore.

2.3 Assembly Methods

After fabrication is complete, individual components must be assembled together in various stages to build an aircraft. The major tasks in the assembly of aircraft components can be categorized as drilling, fastening, sealing, inspecting, and material handling. Fastening, also called filling, includes bolting and riveting. A series of fasteners that connect two or more components are known collectively as a joint. Welding, soldering, and other assembly methods are less common in aircraft construction and are omitted from this discussion.

2.3.1 Drill and Fill

Bolts and rivets are the primary means of attachment in aircraft construction. Holes must be drilled and the correct size and type of fastener must be used to carry and transfer loads through the structure. The location of holes and fasteners relative to other component or assembly features and relative to other holes impacts the stress on the material. The distance from the center of a hole to the nearest edge of a material is known as the edge margin. The correct edge margin is determined by part thickness, hole or fastener diameter, and by the type of load and structural failure (critical load) whether shear, bearing, fatigue, or corrosion. Loads carried through structures with holes produce stress concentrations on the edges of the holes. The edge margin (d_e), hole diameter (d_h), material thicknesses (h_1, h_2), and maximum stress (σ_{max}) are shown in Figure 2.1 along with a depiction of the increase in stress at the edge of the hole. The distance between the center of adjacent holes or fasteners is known as the hole spacing. Holes that are spaced too closely together result in excessive stress concentrations that reduce the fatigue life of the part. Holes that are spaced too far apart increase the load carried by each fastener as well as the likelihood of material failure. Acceptable hole spacing is usually a function of hole diameter and material thickness.

Holes on the exterior of aircraft surfaces are usually recessed or countersunk to create a flush surface. Non-flush surfaces contribute to aerodynamic drag and negatively impact aircraft performance. It is therefore important to use the correct countersink depth to avoid fasteners that are too high or too low. Figure 2.2(a) shows a countersink profile

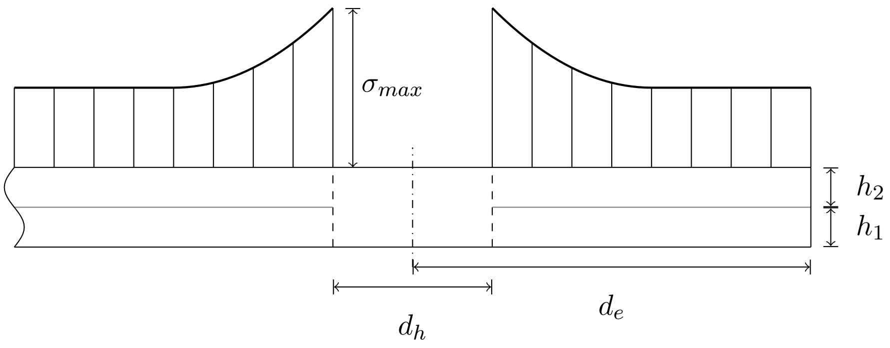


Figure 2.1: Stress distribution and edge margin

in relation to the thicknesses, h_1 and h_2, of two materials. Figure 2.2(b) depicts a hole with countersink, where d_h is the hole diameter, d_c is the countersink diameter, α is the countersink head angle, and h is the height or depth of the countersink. The depth of the countersink must be appropriate for the thickness of materials being fastened. Countersink fastener flushness is particularly important for laminar flow areas. Laminar flow is smooth, parallel flow characterized by the absence or minimization of turbulence or eddies in the boundary layer. The boundary layer is the region of air flow closest to the aerodynamic surfaces of the aircraft. Laminar flow is particularly advantageous on lifting surfaces and the engine nacelle inlet because of the potential for reductions in aerodynamic drag. Achieving fastener flushness in these areas becomes especially important.

Another consideration for drilling holes is the material itself. Material properties impact the type of drill bit or cutter to use as well as the speed of rotation, the applied thrust, and the rate at which the drill is fed or plunged into the material. Harder materials require lower spindle speeds and higher feed rates to prolong cutter life and prevent overheating. Prolonged cutter life and temperature control are also facilitated by careful design of the cutter geometry [27].

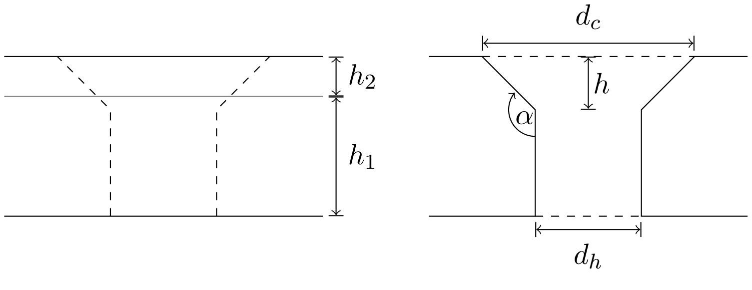
When different materials are stacked up next to (or on top of) each other, several factors must be considered. It is preferable to drill through the harder material first to avoid pulling chips of the harder material through the softer one. This avoids the formation of gouges or bites inside the hole bore. When a soft material and a hard material are stacked up against each other and the softer material is an aerodynamic surface, there is a need to countersink and install a flush fastener from the side of the soft material. This necessitates drilling through the soft material first and risks pulling hard chips through the softer material. One approach to minimize the gouging of the softer material is to utilize peck drilling [27, 28]. Rather than drilling through the material in one shot (positive feed) at a constant feed rate or force, peck drilling involves the repeated axial advancement and retraction of the drill bit to prevent overheating and to allow for better evacuation of chips.

Physical and operational parameters of the drill and bit also impact the severity of burrs formed when the drill enters or exits the stack of materials [27]. After drilling, parts are traditionally separated and the chips and burrs are removed, afterwhich the materials are rejoined and the holes lined up before the fastener is inserted. Special attention to drill parameters can minimize the occurrence of inter-laminar and exit burring, and prevent the need to deburr in some cases. Exit burring can also be controlled by providing backside clamp-up that provides support underneath the final layer of material. Without backside clamp-up, drilling from a soft material to a hard material may result in the cutter pushing the hard material away from the interface with the soft material, creating a gap. This also creates a risk of chips or burrs getting trapped in between the materials at the interface if they are not separated.

Types of Fasteners

There are many types and styles of fasteners used in aircraft assembly. Each fastener is designed to carry a certain type of load for a particular size and length of hole. Fasteners are selected to satisfy fatigue safety margins, ultimate load requirements, the need for permanent or removable fasteners, or other design criteria such as corrosion resistance or electrical bonding. Figure 2.3 shows the major fastener types discussed here. The most common and well-known aircraft fastener is the rivet. Rivets are comprised of a head and a smooth shank with no threads. After insertion, the foot of the rivet is bucked or squeezed to produce a button on the backside. Some rivets, such as blind rivets, rely solely on a squeeze mechanism. Rivets generally rely on plastic deformation for a proper fit and are therefore mainly used with metals, although some blind rivets may be used in composites. Using traditional rivets on composite materials may result in delamination, disintegration, or fracture. Rivets provide minimal clamping force and are typically used for shear loads.

Unlike rivets, bolts have a smooth shank near the head and are grooved or threaded



(a) (b)

Figure 2.2: Countersink characteristics

near the foot. Bolts are fastened with a nut or collar that applies a compressive load to the material stack-up. Traditional bolts with nuts generally require torque wrenches to ensure the correct application of axial compressive force. This applied load guards against shearing and vibration that leads to component fatigue. Similar to traditional bolts, lockbolts have special collars that are swaged or compressed into place, permanently deforming the collar.

Another common fastener used in aircraft assembly is the Hi-Lok[‡]. Similar in appearance to a bolt with a smooth shank and threaded end, Hi-Lok fasteners are designed to guarantee the correct application of torque. Special collars with a narrow neck are designed to shear in two at a predefined torque value. Hi-Lok collar installation removes the need for a torque wrench and independent verification of the correct torque value.

In addition to those discussed here, there are various specialty fasteners. Blind fasteners, for example, are designed to be installed with access to only one side of the material. This is useful for enclosed or confined spaces. Nut-plates are stamped sheet metal with a hole for the fastener and two holes for rivets that attach it permanently to the backside of the structure. This is useful for limited access areas (confined spaces) or where frequent access is necessary (e.g. maintenance doors).

Fastener heads come in two styles, protruding and flush, and are shown in Figure 2.3. The underside of the head of a protruding fastener rests on the surface of the part and the entire thickness of the fastener head extends or protrudes from the surface. Holes for protruding head fasteners are straight, not countersunk. Flush head fasteners are inserted into countersunk holes. The top of the head is nominally flush with the material surface. If the countersink is too deep or too shallow, the fastener head will not be flush with the surface and the head may need to be shaved (countersink too shallow, head exposed) or filled (countersink too deep, head recessed) with sealant. Flush head fasteners are of great importance for exterior aerodynamic surfaces where protrusions contribute to drag and negatively impact the performance of the airplane.

Fastener Size

The grip length of a fastener is the length of the smooth, non-threaded or non-grooved, portion of the shank, as shown in Figure 2.3. Fasteners come in discrete lengths and are assigned a range of material thickness for which each length is appropriate. The length of the threaded portion is one and one half times the diameter of the fastener. For parts with variation, such as composites, the material thickness may necessitate a deviation from the grip length specified in the design. The hole and fastener diameters are selected to provide sufficient strength to withstand the loading condition at that location.

[‡] Hi-Lok fasteners are a product of the Hi-Shear Corporation, now LISI AEROSPACE.

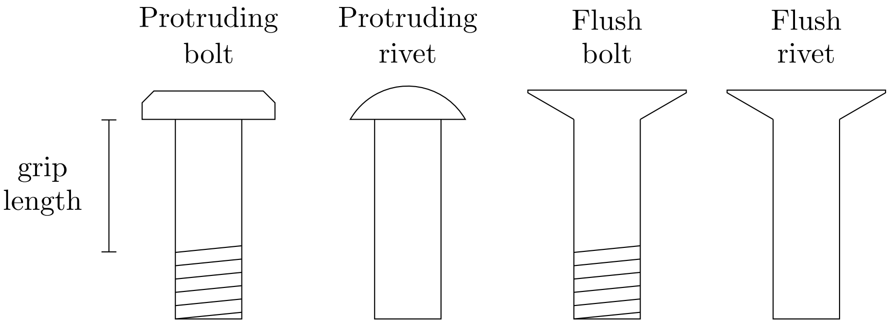


Figure 2.3: Basic fastener types

Fastener Fit

The fit of a fastener in the aircraft assembly impacts the stress around the hole and the assembly process or build plan, including the orientation of parts.

When the diameter of the fastener shaft is nominally the same as the diameter of the hole, this is known as an interference fit. The fastener is held firmly in place by the hole wall and does not allow sliding or rotation. This is also commonly called a press fit. The fastener is installed by force and generates a compressive load on the material surrounding the hole. The compressive load is undesirable for composite materials because it may lead to delamination.

When the diameter of the fastener shaft is slightly less than the diameter of the hole, this is known as a transition fit. The fastener is secured by a light interference fit that allows for rotation under torque but not free rotation. This also facilitates straightforward fastener removal without the need to drill the fastener out or apply force. The applied compressive load is minimal.

When the diameter of the fastener shaft is much less than the diameter of the hole, this is known as a clearance fit. This is the standard and most common fit for a fastener. The fastener initially rotates freely in the hole and is held in place by gravity or some other means, such as tape. Once the collar is installed, the fastener is clamped in place against the material surface.

2.3.2 Sealant

Sealants are used for various purposes in aircraft assemblies. Assemblies that contain liquids or are located in high-temperature areas usually require the application of sealant. Sealants are also used to protect against corrosion. Dissimilar materials in contact with one another can lead to galvanic corrosion due to the small difference in electrical potential between metal types. In the presence of an electrolyte, such as water, the electrical poten-

		Material
Reactive	1	Magnesium and alloys
	2	Cadmium, zinc, aluminum and their alloys
	3	Iron, steel (except CRES), lead, tin and their alloys
Passive	4	Copper, brass, bronze, copper-beryllium, copper-nickel, chromium, nickel and its alloys, cobalt alloys, CRES, graphite, titanium and its alloys

Table 2.2: Galvanically incompatible materials

tial reacts with the electrolyte in an electrochemical process, such as oxidation, resulting in corrosion. The application of a sealant between two galvanically-incompatible materials insulates the electrical current and prevents corrosion. Typical aircraft materials can be placed into categories according to their susceptibility to corrosion. Typical material combinations that are galvanically incompatible are listed in Table 2.2. Materials from different categories have potential to induce galvanic corrosion when placed in contact with one another. Aluminum and low-alloy steels are most susceptible to corrosion [4]. Magnesium is also highly reactive but is no longer used in commercial aircraft. Composites with carbon or graphite fibers can lead to galvanic corrosion in proximity to aluminum. Table 2.3 lists fasteners that are typically used for material stack-up combinations [6].

Most sealants are composed of two compounds that must be mixed to become active. Once active, sealants have a finite working life that is typically eight hours for structural sealants and four hours for fire retardants. It is possible to pre-mix sealants and store them at low temperatures for future use.

Sealants are potentially used at all material interfaces. Although they are generally applied at the interface of dissimilar materials, fire and leak protection zones may require sealant even for similar materials. The major types of sealant application are discussed below.

Fay Seal Flat-surface to flat-surface sealant used between galvanically incompatible materials to prevent corrosion. Typical areas for application are the skin and stringer, the skin and shear-tie frame, skin splices, and doublers.

Fillet Seal Sealant applied to a non-filleted interior corner that effectively creates a fillet. Fillet seals are usually applied in conjunction with fay seals and may be formed by simply running one's finger along the sealant that squeezes out from the fay seal when the materials are clamped together. In fire protection zones, fillet seals may be applied to the

First Material	Second Material	Fastener Material
Alloy steel	Alloy steel	Alloy steel CRES Titanium
Aluminum	Steel	Alloy steel CRES Titanium
	Titanium	CRES Titanium
	CRES	CRES Titanium
	Aluminum	Aluminum Alloy steel CRES Titanium
CRES	CRES	CRES Titanium
Titanium	Titanium	CRES Titanium
	CRES	CRES Titanium
Carbon fiber	Carbon fiber	CRES Titanium

Table 2.3: Galvanic compatibility

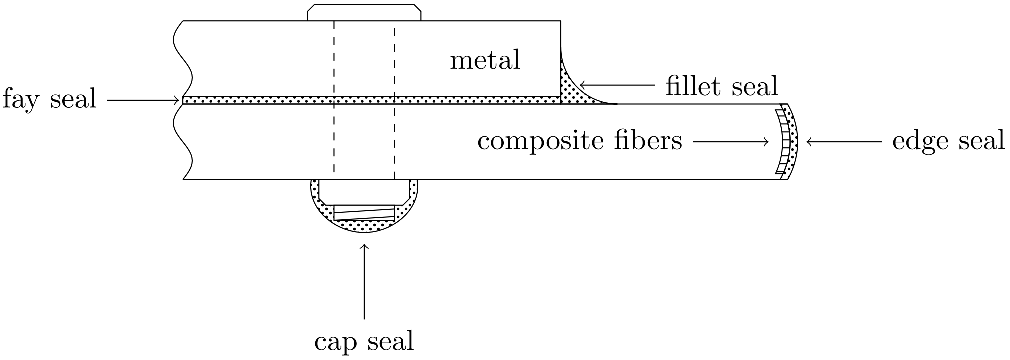


Figure 2.4: Common types of seals

interface even between galvanically similar materials (such as titanium) to prevent high temperatures from permeating and traveling between the parts.

Edge Seal Sealant or resin applied to exposed composite fibers. In carbon fiber-based composites, the exposed graphite fibers may lead to corrosion of nearby aluminum, even if not in direct contact.

Cap Seal Sealant applied to the exposed foot of a fastener and its attached collar. This is especially useful for leak protection for areas such as fuel tanks.

Wet Install

Sealant applied to a fastener before it is inserted into a hole. Wet installed fasteners are primarily used for clearance fit installations rather than interference fit. In an interference fit, the absence of a gap between the shank of the fastener and the hole wall results in any applied sealant being scraped off during hole entry.

There are three methods to apply sealant to a fastener. The first method of wet installation requires sealant on the underside of the fastener head or on the exterior material surface below the fastener head. The second method requires sealant along the length of the fastener shank but not under the head. The third method requires sealant on the fastener collar or on the interior material surface under the collar.

2.3.3 Inspection

Aircraft manufacturing has a long tradition of comprehensive and exhaustive inspection. In addition to the requirements imposed by regulation, inspection is used to ensure that fabrication and assembly operations (especially in critical areas) meet the engineering design specifications. Incorrectly installed components can lead to unexpected stress, fatigue, and component failure—the results of which can be catastrophic.

Inspectors may check for correct placement of parts, hole quality, torque application, fastener flushness, sealant integrity, or many other assembly characteristics. The most basic type of inspections are visual inspection and part verification. The inspector verifies that a particular component has the correct serial number, is in the right orientation, or is in the appropriate stage of assembly. Visual inspections are similar to mental checks for consistency but require paperwork that document the correct parts flowing through the build plan in the correct order. Visual inspection may also check for visible damage to parts—such as tool marks, dents, and dings—or for missing hardware, such as holes without fasteners.

Another type of inspection is the tactile test. The inspector may manually check the surface of a part, for example, to verify smoothness and fastener flushness. The finger or hand test may be used to judge the quality of a repair on a metal or composite surface. The result of this type of inspection, as with visual inspection, may be dependent on the individual inspector [34].

Sealant inspection also falls into the category of subjective inspection. Sealant application is vital to the longevity of components and the prevention of corrosion. The application of sealant is often done with a brush or a roller. The inspector checks for bubbles or other indications of uneven or inadequate sealant.

Hole quality can be measured by a variety of characteristics.

Diameter Hole diameter is measured at 90° offsets. Holes that are too big or too small impact the stress on the material and on the fastener installed in the hole.

Angularity Non-perpendicular holes lead to fasteners with high and low edges. They also suggest misalignment of mated parts and may lead to or be a symptom of elongated holes that lead to stress and fatigue problems.

Countersink depth Countersink depth can be measured directly or indirectly. The direct method involves measurement of the distance from the material surface to the bottom of the countersink. The indirect method involves measurement of the outer diameter of the countersink on the material surface, from which the depth can be calculated using the known countersink angle.

Taper Holes with varying diameter may be problematic for fastener insertion. Furthermore, the stress concentrations around holes are dependent on the hole diameter and tapered holes may result in non-uniform stress through the part.

Burr severity The height and size of burrs impact the fatigue life of the material. Small burrs are preferable to large ones.

Bore smoothness The roundness of the hole bore is dependent on the cutter (drill bit). Out-of-round hole bores may indicate high stresses and work hardening of the part.

Another issue aside from individual hole quality is the potential for elongated, oblong, or “snowman” holes not related to angularity. This can occur when previously drilled holes such as pilot holes are reamed to full size. If the holes on the various part stack-ups are not aligned properly, an off-center hole may result in one or more layers.

The records of inspection are an important part of the aircraft assembly process. The records stand as evidence of adherence to the production certificate and the type design, and lend confidence that each instance of the aircraft will perform as designed.

2.3.4 Tooling and Material Handling

Material handling and component movement are important steps in the build process. Particularly for external-facing parts, great care must be taken to prevent scratching, denting, or otherwise marring the surface and this may require special tooling. Commercial aircraft structures are generally large and relatively lightweight. This results in components that are flexible and subject to deformation. These characteristics are desirable because aircraft structures bend and deform predictably under flight loading conditions. This same flexibility, however, can be a challenge during assembly. Large components without rigid structural supports may deform or bend under their own weight. It is necessary, therefore, to employ tooling and material handling fixtures that minimize the impact of this flexibility on the build process.

Various tools are used to handle and move aircraft parts. Overhead cranes are capable of lifting and moving entire fuselages or wing sections. These cranes are often installed on rails attached to the main load-bearing walls of a building. Smaller overhead cranes can also be used. Cranes usually attach to special purpose attachment points that help minimize flexing and deformation of parts under transport.

Assembly fixtures are used to hold components in place and to position and support the workpiece. Fixtures ensure that produced parts conform to a shape or orientation and provide interchangeability. Fixtures allow the operator to securely and repeatably locate part features.

Jigs are purpose-built, custom tools that allow repeatable, accurate guiding of tools during manufacture. Jigs are used in conjunction with fixtures and in some cases a jig is also a fixture. An example is a drill jig that acts as a template and facilitates locating and drilling properly oriented holes. Other jigs, such as assembly jigs, facilitate the accurate placement of parts in relation to one another.

2.4 Tolerance

Tolerance plays an important role in aircraft design, fabrication, and assembly. Improper or inappropriate tolerances may result in parts or components that do not fit together correctly. Tolerances are additive and extreme cases must be considered. For example, two parts that are intended to interface may both be fabricated with a given tolerance, $x \pm \ \delta$. If the first part falls on one end of the tolerance at $x + \delta$ and the other part falls on the opposite extreme at $x - \delta$, the result is a difference of 2δ. This buildup of tolerance is very important and must be considered in the assembly process. A third part interfacing with the first two would need to allow for a 2δ variation in location. Holding tighter or smaller tolerances is more costly because the equipment and tooling to fabricate high tolerance parts is more complicated and difficult to design and develop. In high-tolerance applications, the impact of temperature and other environmental factors must be considered as well [15]. For this reason, it is common to have environmental controls for temperature and humidity. In some cases, thermal expansion and contraction may be utilized to attain the proper interference fit between adjacent parts.

Just as tolerance builds up or accumulates in the design, tolerance is consumed during assembly. When parts are firmly attached one to the other, the positional fix reduces the tolerance available for another attachment point. This may lead to wrinkles or to parts that will not fit together at all. The order of installation of fasteners impacts this washout as the tolerance gap is closed.

Summary

Familiarity with aircraft fabrication and assembly techniques provides context for a discussion of automated assembly. Material properties, fabrication methods, and assembly approaches are interrelated. As such, a selection of any one of these may impose constraints on the choices for the other two. In terms of automation, material selection and fastener type are particularly important. The ability to automate certain tasks is dependent on fastener type which is dependent on material selection and the structural loads experienced at each joint.

Chapter 3

Automated Assembly of Aircraft Components

The commercial aircraft industry has long been dominated by low production volumes, long product life cycles, and slow ramp-up rates. These factors have contributed to the overwhelmingly manual nature of aircraft production despite advances in automation over the last 50 years. The reliance on manual operations contributes to high variability that limits efficiency and production throughput. Large capital investments in robotics are more easily justified for large volume production runs. The automotive and electronics industries—with high production volumes, short product life cycles, and rapid ramp-up rates—have utilized automation extensively for decades to improve quality and increase throughput. Recent breakthroughs in customizable automation such as 3-D printing have highlighted the ability to use computer-controlled automated machines to fabricate and assemble even low-volume aircraft components [2]. While automation becomes more feasible in low-volume production, some commercial aircraft models are experiencing demand that necessitates increased production volumes. Furthermore, competitive pressures have refocused manufacturers on reducing cost and improving quality. Together, the case for automation in aerospace manufacturing is becoming stronger. Decisions to implement automation, however, are often not aligned with manufacturing strategy and are of an ad hoc nature [18]. Often, automation decisions are made in the absence of a coherent automation strategy. Such decisions result in semi-automated systems that employ sub-optimal levels of automation because the support for automation decisions is poor.

This chapter aims to document the challenges that automation addresses and how to improve the support for automation decisions by understanding the problems it solves and the challenges involved in its implementation. This chapter begins with an overview of the reasons for, and benefits of, automated assembly. Automation has the potential to reduce individual task times and eliminate some tasks needed in manual operations. Together, the elimination of some tasks and the shorter duration of others yields reduced overall touch

Decrease number of quality defects
Mitigate impact of labor shortages
Minimize awkward and repetitive motions
Eliminate dull, dirty, and dangerous tasks
Increase throughput and capacity
Reduce human error

Table 3.1: Benefits of automation

times. Reduced manual touch time leads to lower cost; reduced automated touch time (and thus total touch time) allows greater throughput and a higher production rate. This is followed by a discussion of robotic and non-robotic automation, the case for and against each one, and some examples of implementation.

3.1 Overview

Automated assembly techniques are desirable for multiple reasons. Automation can reduce repetitive or awkward motions for workers, improve repeatability, and mitigate the impact of tasks subject to human error. It can eliminate dull, dirty, or dangerous work. Automation can lead to leaner operations, higher production rates, and lower costs. It can facilitate higher efficiency and greater flexibility. Furthermore, machines do not need lunch breaks and do not get tired (unplanned maintenance notwithstanding). For the most part, modern automated machines have mean time between failure (MTBF) of 80–90 thousand hours [30]. Table 3.1 provides a summary of the benefits attributed to automation [18].

3.2 Task Time

As summarized in Section 2.3, major aircraft assembly tasks include drilling, countersinking, fastening, sealing, and material handling. Some tasks required during manual operations, such as separation and deburr after drill tasks, can be eliminated when using automation [31]. Manual drilling and fastening methods traditionally require the separation and deburr of components to minimize gouging and inter-laminar burrs that lead to part separation. One approach to reduce the number of tasks involved in drilling and fastening eliminates the need to separate and deburr[*] by maintaining part clamp-up and carefully controlling drill bit geometry and operational parameters [26]. This approach has the potential to reduce the fatigue life of parts and the impact of its use on airplane performance must be assessed. This controlled process reduces—but does not eliminate—the creation of burrs, the impact of which can be predicted due to the repeatability of

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[*] This is also known as one-up assembly.

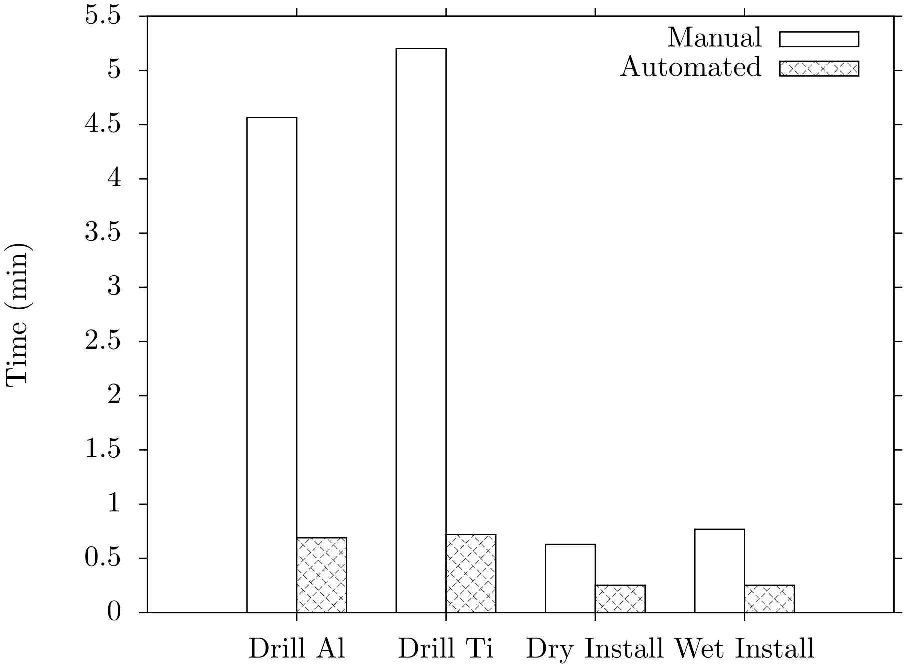

Figure 3.1: Comparison of individual task times

the equipment. Separation, deburr, inspection, realignment, and fastener insertion can account for approximately one-third of the task time. Consolidation of drilling, reaming, and countersinking along with automated cycle-time improvements contribute the remainder of the time savings.

Automated cycles times are often significantly less than that required by manual operations for the same tasks. Figure 3.1 shows a comparison of individual task times for manual versus automated operations as measured in practice. Wet install fastening times include sealant application (see Section 2.3.2) while dry install fastening times do not. Manual drill times include positioning, drilling, reaming, countersinking, and deburring. Part separation prior to deburr is done on a per part, not per hole, basis and is not included in the manual task time. Automated drill times consolidate drilling, reaming, and countersinking and do not require separation or deburr. Move, inspect, and sealant task times (excluding wet install) have been omitted due to high variability, uncertainty, and lack of data. Drill and countersink task times, on either aluminum or titanium, are reduced by approximately 85% while wet and dry fastener installation task times are reduced by approximately 60–70%. Additionally, initial setup times may also be less for automated systems.

Of the tasks shown, drill and fasten tasks have the greatest potential for gains in cycle time [31, 32]. These operations also have the greatest potential for improvements in quality due to the high degree of repeatability in automated systems. Hole quality, for example, can be measured by many characteristics including diameter, bore smoothness, angularity, taper, (countersink) depth, and burr severity or prevalence (see Section 2.3.3). These hole characteristics can be controlled by cutter geometry, feed rate, cutter speed, and pecking, among others (see Section 2.3.1). Highly accurate and repeatable systems can control these factors with great precision, whereas the performance of human operators is much more susceptible to variation caused by fatigue, lack of attention, lack of skill, or simple differences in human strength, accuracy, and steadiness [34]. Even small gains in efficiency and quality can have significant impacts when the number of operations are considered. This is easily understood when one considers the number of fasteners in a commercial aircraft [32]. The Boeing 787 Dreamliner, for example, has approximately eight thousand exterior holes and fasteners for each of six sections of the fuselage. Without considering fasteners on the wing, empennage, or nacelle, a one-second reduction in task time has the potential to save over 13 hours of touch time.

The number of holes and fasteners required is dependent on the design philosophy for the aircraft. As described in Section 2.3.1, hole spacing is a function of material thickness and fastener diameter. The material thickness and number of required fasteners offer a trade-off between structural weight and number of assembly operations.

3.3 Touch Time

The relative frequency of each task within an assembly operation impacts the potential time savings from automation. Figure 3.2 shows a comparison of total estimated touch times for manual and semi-automated inlet assembly broken down by task. Note that the times shown include setup times. Depending on the operation, there may be no setup, one setup, or recurring setups for calibration or consumable parts and equipment. Details of the assembly tasks used for this analysis are described in Section 4.1. The estimate for semi-automated assembly is based on the automation of the majority of drill and fill operations with additional room for improvement in move, inspect, and seal tasks. The touch time here is defined as the sum of all time spent by independent agents (human or machine) working on the assembly. If two agents each work on the assembly for 10 minutes (even simultaneously), for example, the total touch time is 20 minutes. This is different from flow time, or clock time, required to complete a task, which may be reduced by increasing the number of agents working in parallel. Manual touch times account for separation, deburr, and inspection before realignment and fastening. Figure 3.2 also shows the estimated cumulative effect of the reduced touch time on overall inlet assembly process time. The manual touch time is reduced by 70%. Some of the manual touch time is replaced by automation touch time and results in a total touch time reduction of 30%.

The touch time required to produce an assembly decreases as experience is gained

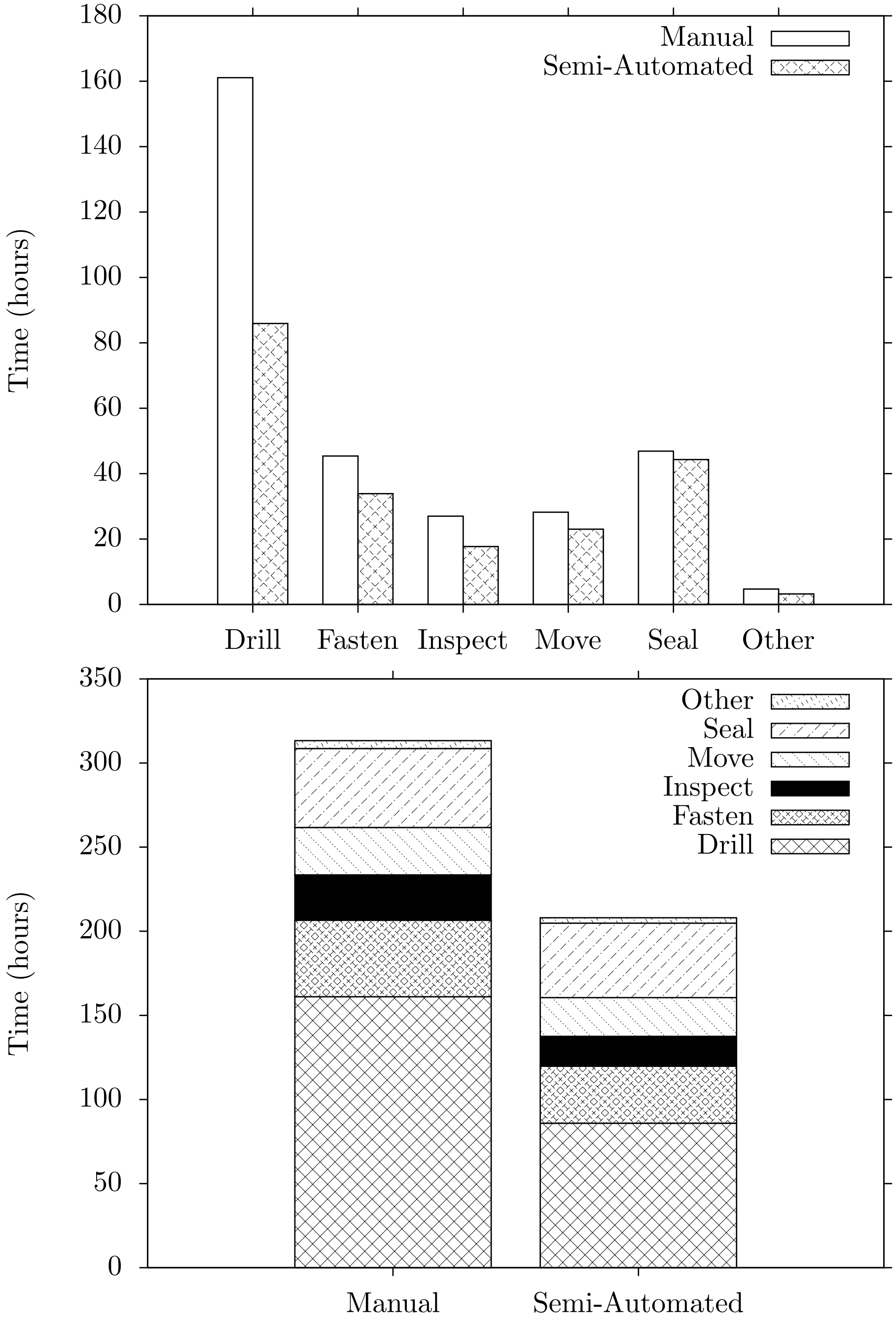

Figure 3.2: Inlet assembly touch times by task and method

Unit	Time
1	100
2	80
4	64
8	51.2
16	40.96
$\vdots$	$\vdots$
2^{n-1}	$t_1 p^{n-1}$

Table 3.2: Estimated touch time, $p = 0.8$

and as efficiencies are realized. The learning, or experience, curve is modeled as a power function [35] (see Equation 3.1) where t_x is the time required for the current unit of production, t_1 is the time required for the first unit of production, x is the cumulative number of units produced, and p is a number between zero and unity (the percentage).

$$t_x = t_1 x^{log_2(p)} \tag{3.1}$$

The percentage represents the relative time required to perform a task after twice as many units are produced. Table 3.2 lists unit numbers and estimated times for an 80% experience curve. Figure 3.3 shows several experience curves referenced to 1000 units. The reference value is the number of units at which touch times are estimated or standardized. For production units below the reference value, extra time is allocated to work through startup problems and achieve a stable operating rhythm. For production units above the reference value, additional efficiencies are expected, the magnitude of which is dependent on the nature of the task(s) and is reflected in the type of experience curve. The time required for the first production unit can be determined by solving Equation 3.1 for t_1 and substituting the reference value and its standard time.

$$t_1 = \frac{t_x}{x^{log_2(p)}} \tag{3.2}$$

The impact of experience curves is less significant for automation. Operators and support personnel may identify improvements that reduce cycle time or eliminate waste, but the automated equipment ideally performs the job consistently and repeatedly; in other words, it follows the exact same steps and completes them in the exact same time, every time. One would expect, then, that the experience curve for automated assembly is more shallow than the experience curve for manual operations. The experience curve for a sample semi-automated system is also shown in Figure 3.3. Note the difference in the range of x-axis from the baseline experience curves. The total touch time is the sum of the manual and automated touch times adjusted using the respective experience curve. Only

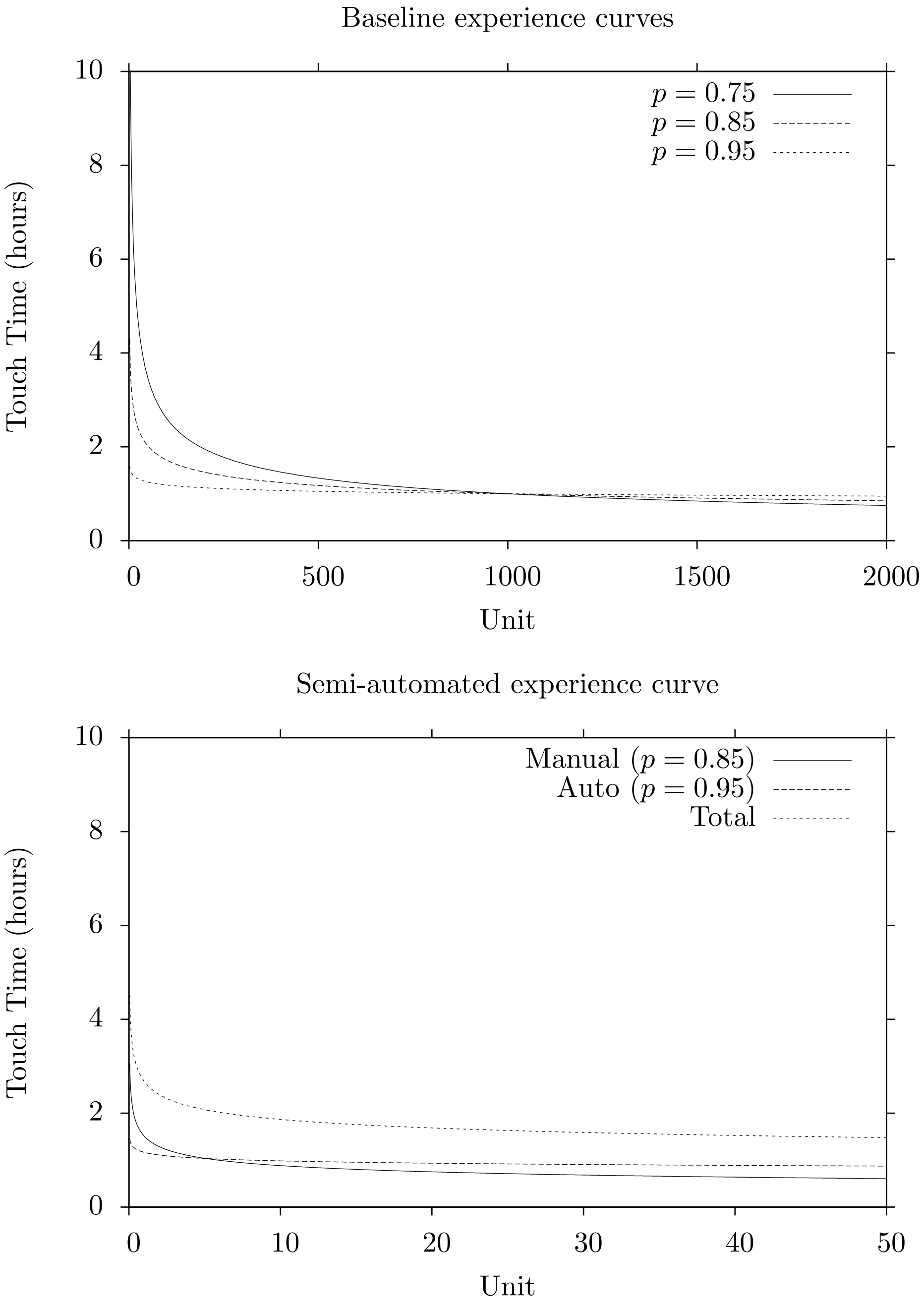

Figure 3.3: Baseline and semi-automated experience curves

a portion of the tasks are subject to the manual experience curve, while the remainder are subject to the automated experience curve. Experience curves highlight the necessity of iterative improvement through trial and experimentation, even with automated systems.

3.4 Challenges

The difficulties of successfully implementing automation in aircraft fabrication and assembly have been addressed by McAfee [20], McCarville [21], Herrera [13], Jayaweera [16], and Webb [33]. Automated processes can succeed or fail depending on various factors. Foremost among them is the recognition that automation is a process, not simply a machine [29]. Technical limits, upstream process unreliability, and component variability can render the automation ineffective. Human-machine interface problems, supply chain or just-in-time (JIT) issues, and workforce disengagement can cripple the system before it has a chance to prove itself [18]. Robots are not mechanical people; they are parts of an integrated manufacturing system [34].

Automated assembly generally relies on consistent inputs to the automated process. Upstream variability in component size, orientation, thickness, or relative position can cause incorrect assembly, loss of product, and damage to equipment. It is of paramount importance to maintain consistency among engineering specifications, automated programming, and the actual condition of the assembly. The addition or removal of seemingly innocuous parts such as clips can cause collisions with automated equipment, especially if equipment moves along a pre-programmed route. Inconsistent installation of temporary fasteners, especially with excessive angularity due to tolerance washout, can cause elongated holes that impact structural integrity.

Operators and support personnel can also reduce the effectiveness and efficiency of automated machinery by working around the system rather than with it. Operator familiarity with manual workarounds, traveled work (work that must be completed out of sequence), and custom fixes can undermine the effectiveness of automation. For example, if inputs (upstream parts) to the automation are inconsistent in size, shape, orientation, or thickness, operators (and other support personnel) should seek to remedy or address the variability in upstream components rather than making arbitrary adjustments that mask the existence of a problem. Examples of custom fixes include shimming, shaving, prying, or modification of automated programming routines to accommodate individual components. This is a basic principle in lean operations and process improvement. Furthermore, misaligned incentives and distrust among vendors, operators, technicians, and management can result in ignored warnings, unaddressed errors, reduced operational effectiveness, misplaced blame, and poor accountability [30].

3.5 Non-robotic Automation

Improved quality is often realized by reductions in the number and severity of defects. The excellent repeatability required to achieve improved quality has resulted in the proliferation of custom-built, special-purpose monuments wherever automation is implemented in aircraft assembly. Non-robotic automation, or the so-called monument, is widely understood to be large and stationary equipment.

Monumental machinery provides several advantages over manual labor in the aircraft assembly process. First, the nature of large, heavy, and stationary equipment provides rigidity and a fixed positional reference for locating parts [29]. Rigidity leads to greater positional accuracy that is necessary for the tolerances required in aircraft assembly. Second, the size of monumental equipment matches that of the aircraft. This may be perceived as advantageous in that equipment reach is not a concern and machinery may be considered “right-sized” for the assembly. Third, special-purpose equipment generally performs extremely well on the task for which it is designed. It can be optimized to take advantage of peculiarities in the process or to perform well for a narrow set of tasks.

Unfortunately, non-robotic automation, or monuments, also present certain disadvantages. First, monuments are fixed in capacity. Tasks are generally performed serially (single agent) and increases in production rate cannot be accommodated without adding additional monuments that require floorspace, large amounts of capital, long lead times, and perhaps changes in factory layout. The fixed capacity of the equipment increases the likelihood that a monument constrains production throughput and becomes a bottleneck in the factory [33]. Second, monuments are expensive. Addressing the capacity issue by purchasing additional units may not produce an acceptable return on investment. The high cost of capital equipment can reinforce capacity constraints. Third, monuments are not particularly flexible. Once its task is complete, monuments cannot be re-tasked to perform additional functions. The special-purpose nature of monuments makes them difficult to modify even when their functionality does not meet original design intents. Aircraft design and build improvements may be constrained by the limitations of inflexible equipment. Finally, monuments can take a long time to design, build, test, and install [31, 33]. Monuments are not commodities nor are they mass produced; as such, they do not benefit from economies of scale.

Examples of non-robotic automation in aircraft assembly abound. Table 3.3 lists some of the more well-known installations that have been identified in the literature [16]. Non-robotic automated systems vary widely in purpose, capability, and construction. As such, it is difficult to characterize their capabilities with a single set of descriptions. The Automated Spar Assembly Tool (ASAT) used by Boeing, for example, drills holes for thousands of fasteners in long wing spars. The tool employs dozens of clamps that rigidly hold the spar in place lengthwise. The Horizontal Automated Wing Drilling Equipment (HAWDE) used by Airbus is a four-story high jig that attaches wing skin panels and takes weeks to complete one wing [14]. The Broetje iGantry riveter drills and fastens fuselage section

Automated Spar Assembly Tool	ASAT
Automated Spar Drilling and Fettling System	ASDAFS
Gear Rib Automatic Wing Drilling Equipment	GRAWDE
Horizontal Automated Wing Drilling Equipment	HAWDE
Gemcor Rotary Head Fastening System	—
Broetje iGantry riveter	—

Table 3.3: Examples of non-robotic automation in aircraft assembly

skins to internal frames and bulkheads and takes several days to finish. It employs an inner and outer tool that rotate around the fuselage on a circular frame and traverse the barrel lengthwise. Other than the value-added task performed by each (drill and fasten), these monuments are more different than they are similar.

3.6 Robotic Automation

For the purposes of this thesis, robotic automation is characterized as industrial robotics having articulated arms with six degrees of motion freedom. Robots have been implemented in aircraft manufacturing with varying degrees of success. Robotic automation systems have been deployed at Airbus, Boeing, Bombardier, Dassault, and Grumman [16, 17, 29].

Robotic systems have many advantages. First, robots can perform a wide range of tasks including drill, countersink, fasten, seal, move, pick, place, paint, sand, and sense operations. Consequently, one of the greatest perceived advantages of robotics is their flexibility to perform a variety of tasks using a common platform [31, 34]. Robots can be retasked or assigned multiple tasks; multiple agents can be assigned the same task and work in parallel to reduce flow time and increase production rate [32]. This approach yields higher utilization of assets and reduces the number of robots required to complete an assembly. Second, as robotics continue to pervade manufacturing facilities, economies of scale allow robotics manufacturers to reduce costs. This promises to make acquisitions of robotic systems more attractive. Furthermore, the increasing commoditization of robotics reduces supplier dependence, although there continue to be accuracy and capability differences among vendors. Third, robotic systems are smaller and weigh less than large, stationary monuments. In this sense, robots are “right-sized” for the task. Finally, standard systems require less time to make operational. Lead times consist primarily of production and test rather than extensive design cycles.

Robotic systems also have disadvantages, although advances in technology are overcoming many of them. First, the lighter weight of robotic systems often makes them less rigid [29]. Lower rigidity means lower accuracy because the absolute position of robotic arms and instruments is subject to deflection or deformation under load. As robots perform tasks, small inaccuracies accumulate. Correcting this requires occasional recalibration to known absolute positions. This can be overcome through secondary encoders or additional sensing systems that update and compensate the positioning system with known absolute positioning reference points [31, 32]. Additionally, robots can also rely on determinant assembly features (holes) in components. Second, one size does not fit all applications. Standard-sized end effectors (see Section 3.6.1) may encounter physical access limitations. Medium-to-large part features may inhibit the reach of end effector nosepieces. Confined spaces or small component features may be incompatible with generic, medium-sized equipment. Third, standard robotics accentuate the need to design components and systems to take advantage of the strengths of automated assembly. This often results in simplified design and construction. This is not an inherent disadvantage but does require the design and implementation process to be reconsidered to accommodate the automation. Many of the challenges to implementing robotic automation in the assembly of an engine nacelle inlet are also described in Section 4.1.

3.6.1 End Effectors

End effectors attach to robotic arms to perform the value-added work of assembly. They offer task-specific functionality and represent the flexibility in an otherwise standard platform. In this sense, the end effector is the tool while the robot functions as a universal handle that receives its positional instructions from a control system with knowledge of the build plan. The robot also provides electrical, hydraulic, and pneumatic connections as necessary.

There are two major categories of end effectors. Single-function end effectors perform one task, such as drill, fasten, or inspect. They are relatively simple and low cost. Multi-function end effectors perform many tasks but are much more complex and expensive. A multi-function end effector may be capable of drilling, inspecting, and fastening (with sealant) while maintaining clamp-up force. This eliminates wasted motion and unnecessary second or third passes. Multi-function end effectors are an important element in the discussion of one-up assembly. Ultimately, the organization must decide what is acceptable and whether it meets the design intent of the assembly.

Special-purpose end effectors—whether single- or multi-function—require additional development, production, and testing and are therefore generally more expensive than standard end effectors.

Summary

Automated assembly has the potential to drastically reduce task time 60–85%. This task time improvement can result in manual touch time savings near 70% and total touch time reductions greater than 30%. The impact of touch time savings on flow time may be amplified by parallel operations with multiple agents. Reduced flow time results in increased throughput and enables higher rates of production.

Traditional automation consists of large, stationary monuments that are highly efficient but also highly inflexible. The high costs and inflexibility of monuments has stirred interest in flexible robotics systems that cost less, weigh less, and offer a standard platform for a variety of assembly tasks. Robotic systems have their own challenges, to be sure; despite this, design and build plan changes that accommodate the peculiarities of robotic automation promise to take advantage of lower cost and higher throughput.

Chapter 4

Engine Nacelle Inlet Assembly

Increasing demand for certain classes of aircraft requires ever-higher production rates. The requirement for higher production rates presents the opportunity to incorporate robotic automation into the assembly line in order to ensure quality and consistency at high velocity. The level of automation influences long-term recurring and short-term non-recurring costs including facilities, tooling, robots, and manual labor.

This chapter begins with an overview of the engine nacelle and its purpose as part of the larger aircraft system. The build and assembly plan for an actual engine nacelle inlet is then described. This includes an overview and description of the major components and subassemblies and their features. Each step in the build plan includes a discussion of automation considerations. The build plan is followed by an overview of the proposal evaluation process and the financial justification for implementing a robotic assembly line. While this provides a data point on a curve similar to those shown in Figure 1.2, it is unknown on which curve it lies and whether or not it is optimum from a cost perspective. The data shows, however, that this level of automation results in present value cost savings of approximately $250M.

Nacelle

The nacelle is the aerodynamic covering of the engine. A nacelle—a simplified view of which is shown in Figure 4.1—typically consists of three main components: the inlet, the cowl, and the thrust reverser. The inlet is the leading edge of the nacelle. Its interior diameter generally increases as it nears the entrance to the engine; this reduces the air velocity to an optimal level for compression by the engine. The thrust reverser is a movable component that, when engaged, redirects engine exhaust outward and reverses the direction of the thrust vector to aid deceleration. The cowl is a removable covering that bridges the inlet and thrust reverser and provides access to engine systems. For a more detailed discussion of nacelle components and their role in the overall propulsion system, the reader is encouraged

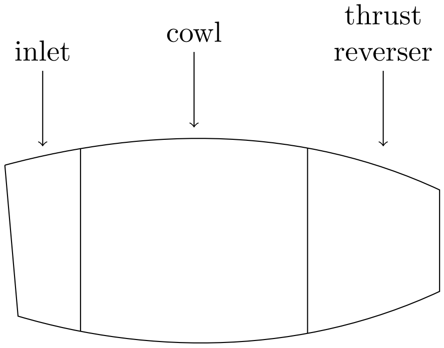

Figure 4.1: Basic nacelle components

to consult a more comprehensive text [19].

4.1 Build and Assembly Plan*

The desired schedule to build an engine nacelle inlet is driven primarily by the schedule to deliver airplanes to customers. The airplane delivery schedule is dependent on the design and manufacture of the various subcomponents. The airplane delivery schedule dictates increases in production rate that are typically phased over a period of years. This long time scale is traditionally necessary to allow for learning and efficiencies to be realized. This is particularly true for manually-assembled components. Experience in manual aircraft assembly has taught that the rate must be gradually increased in order to take advantage of learning to increase efficiency. This conservative approach provides confidence to customers that airplanes can be delivered on schedule because rates are progressively demonstrated. Figure 4.2 shows the first 50 months of the schedule to increase the rate of production [36]. Of particular relevance is the approximately 24 months of production at low rate and the additional 24 months required to reach full rate. The capital investment required to install a robotic automation line is significant. The automated system, even in a phased installation, must be ready prior to the first month but is not fully utilized for another 48 months. This is a prime example of the differences in industry norms that impact the decision to implement automation.

Scheduled airplane deliveries may fluctuate from one month to the next. It is difficult, however, to constantly increase or decrease the rate of production (even by one unit), especially on short notice. It is preferred, instead, to stabilize the rate of production. This allows production in a given month to either lead or trail the number of units to be delivered

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*Some details have been omitted or intentionally changed to protect proprietary information and to simplify the discussion.

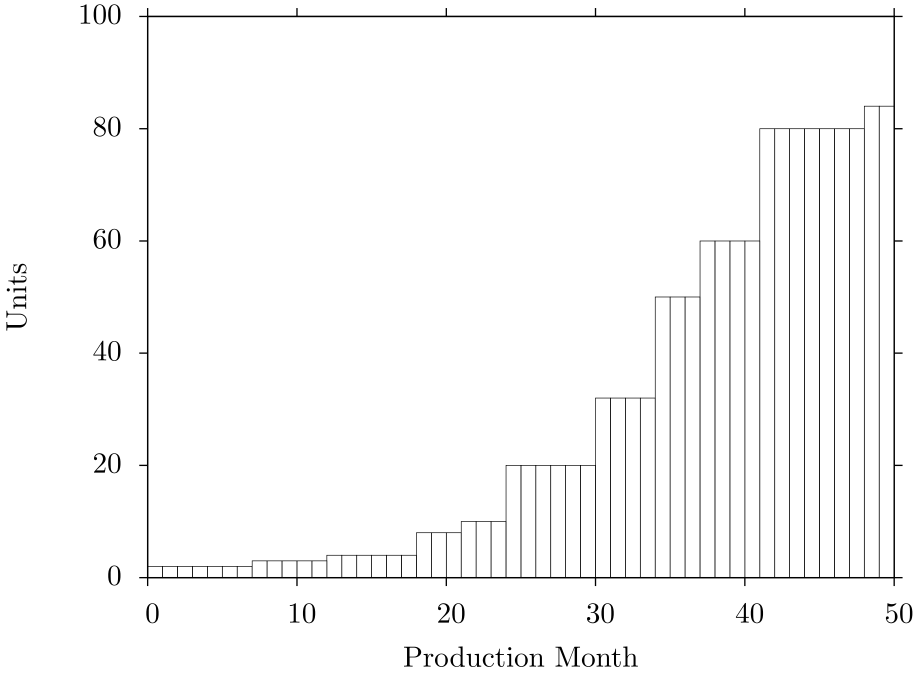

Figure 4.2: Production rate breaks

but to maintain small, changing amounts of inventory that make up the difference. As the rate increases, the system is allowed to stabilize for several months before increasing the rate again on its way toward the long-term rate. Future growth in the market for this particular airplane may necessitate further increases in rate.

The production of any number of inlets per month relies on the successful assembly of the various components in the assembly plan. The engine nacelle inlet is composed of several subcomponents and subassemblies. Binks, Porte, and Shutrump present configurations of nacelle inlet components and materials that are widely used in industry [5, 22, 25]. This pattern is followed here. A composite inner barrel attaches to a ring that in turn attaches to the front face of the engine fan case. The other end of the inner barrel attaches to the inner circumference of the nacelle lipskin. The lipskin is the forwardmost part of the inlet and is exposed to the flowstream. The outer circumference of the lipskin is then attached to the outer skin, or outer barrel. Internal structural support is provided by two bulkheads, one forward and the other aft, which provide radial stiffness. The aft bulkhead is mostly planar while the forward bulkhead is canted forward and fits inside the hollow of the lipskin. The bulkheads attach to the inner barrel, lipskin, and outer barrel via multi-piece chords. The aft bulkhead serves as a firewall and the forward bulkhead provides a closed system for engine anti-ice hot air that is bled from the engine. The nacelle inlet

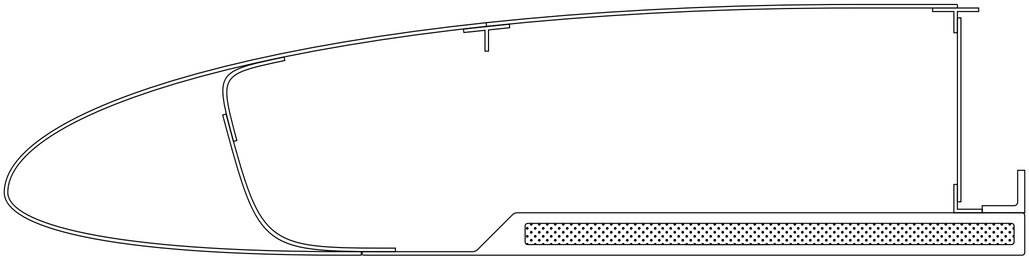

Figure 4.3: Engine nacelle inlet cross section (simplified)

must also provide plumbing, fixtures, and hookups for auxiliary systems such as engine anti-ice, ground cooling, and air support equipment. Although provisions exist for these systems to be routed through the inlet assembly, they will not be discussed nor depicted here.

A cross section of the inlet is shown in Figure 4.3 and depicts the approximate layout of the various components. For the purposes of this discussion, the three-dimensional inlet is created by revolving the cross section around an axis in the plane of the page somewhere below the figure†. This convention is followed by subsequent cross sections provided with each build step. Hole and fastener locations are depicted by dash-dotted centerlines. Each hole location in the cross section represents several hundred holes around the revolved part. Collectively, the holes derived from a single hole designation in the cross section are known as a joint.

4.1.1 Ring to Inner Barrel

The aft end of the inner barrel attaches to the engine fan case via a one-piece ring. The single-piece inner barrel is constructed of a honeycomb core surrounded by layers of CFRP (see Section 2.1). Figure 4.4 shows a cross section of the the inner barrel, the attach ring, and the aft inner angle used to attach the aft bulkhead (see Section 4.1.3). The titanium ring is attached fully aft to the outside of the inner barrel with blind fasteners. The aft bulkhead functions as a firewall and all interfaces and fasteners receive a high temperature sealant to prevent heat penetration.

The titanium chord, or aft inner angle, used to attach the aft bulkhead to the inner barrel is constructed of multiple pieces that are spliced together circumferentially in the same manner as the aft bulkhead (see Section 4.1.3). This method of assembly (splicing) allows the bulkhead to be installed around the inner barrel rather than over the end as was done with the attach ring.

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† Actual inlet designs are often not simple surfaces of revolution.

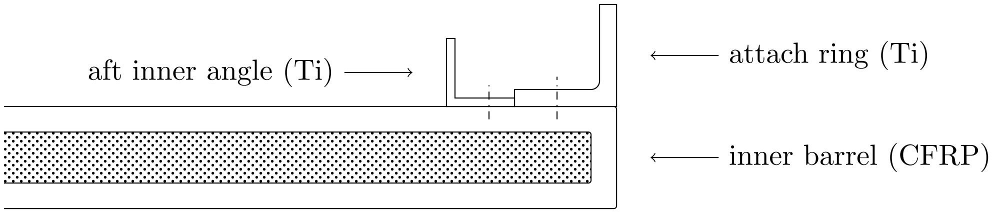

Figure 4.4: Cross section of inner barrel, attach ring, and aft inner angle

Automation Considerations

Composites are typically formed on a tool that provides a fixed reference datum. Variability in composite thickness is an issue but is normally limited to the side opposite the tool. If the local thickness of the composite falls outside the grip range for the nominal fastener length, a shorter or longer fastener must be used instead (see Figure 2.3). The composite inner barrel is laid on top of a honeycomb core rather than on a tool. This results in variable thickness on both sides of the barrel. The composite thickness must be measured to ensure the correct fastener length is used. Automated systems typically measure this thickness by determining the distance between the upper and lower tool using backside clamp-up. The blind nature of the fastener installation precludes normal backside clamp-up and thus requires a different approach to measure the correct fastener grip length. Simple manual tools exist but automated probes would likely have trouble with the honeycomb core. Other solutions may involve the use of thrust or torque monitoring to determine material entrance and exit points.

4.1.2 Multiple-piece Versus One-piece Lipskin

Typical engine nacelle inlet lipskins are assembled from multiple pieces using splices. This is common on many aircraft programs and the approach has several advantages. First, shipping and transport are easier because the parts are smaller and more easily packaged. Second, during attachment of the lipskin to the forward bulkhead (see Section 4.1.4) or the outer barrel (see Section 4.1.6), a multiple-piece lipskin provides some flexibility to mitigate variabilities in the other components. The size of the gaps between lipskin pieces and the exact orientation of each allows for a custom fit each time. The disadvantage of this approach is that extra work is required to cut the one-piece machined lipskin into multiple pieces and also to reassemble it. There are additional parts required (splices and fasteners) that add weight and cost. The gaps at the splice joints also contribute to aerodynamic drag.

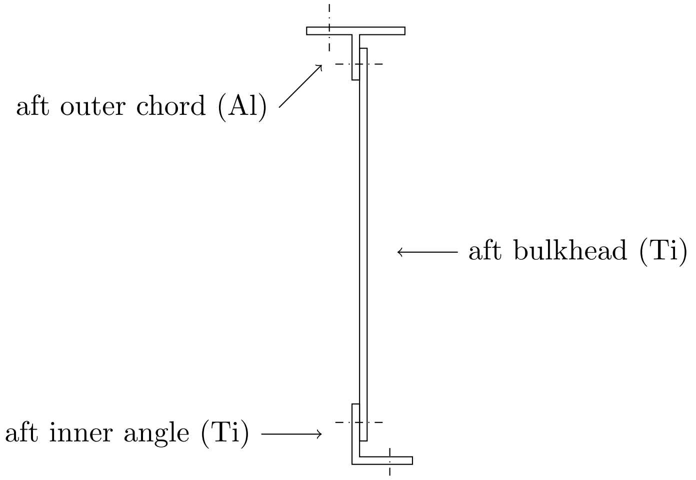

Figure 4.5: Cross section of aft bulkhead, aft inner angle, and aft outer chord

Furthermore, the extra handling of the lipskin pieces present opportunities for damaging, denting, or marring the surface.

An alternative to the multiple-piece lipskin is a one-piece lipskin. There are additional challenges and expenses involved with shipping and transport of a one-piece lipskin but the gains become a contributor to airplane performance. The use of a one-piece lipskin eliminates touch time, tooling, part count, and weight, all of which reduce cost. The one-piece lipskin also becomes a critical ingredient in meeting laminar flow requirements by reducing drag caused by the interface at the splice joints as well as the fasteners used to attach the splices to the lipskin.

4.1.3 Aft Bulkhead

The aft bulkhead provides radial stiffness and supports the outer barrel or skin (see Section 4.1.6). It also acts as a fire barrier and can be made of titanium to withstand high temperatures (see Section 2.1) [5, 22, 25]. The aft bulkhead is often assembled from planar elements that extend radially from the inner barrel. These elements attach to the aft inner angle on one end and to the aft outer chord on the other. Figure 4.5 shows a cross section of the aft bulkhead, the aft inner angle, and the aft outer chord. The elements of the outer chord are attached to the outer circumference of the elements of the aft bulkhead. A high-temperature sealant is applied to joints and interfaces to ensure the integrity of the aft bulkhead as a fire barrier. The sealant requires constant clamp-up that necessitates threaded fasteners such as Hi-Loks. Elements are joined using splices and are placed around the barrel and attached to the inner angle using fasteners with sealant.

Automation Considerations

Sealant application is challenging for automation. Automated paint spraying has been successful in dedicated booths but sealant must be applied at various locations during assembly and booths would complicate the process. Furthermore, fillet, edge, and cap seals (see Section 2.3.2) are typically applied with brushes and rollers and no automated solution exists to replace them.

The small size of the aft outer chord may present a challenge for some end effectors to access the space. The vertical stiffener may not provide sufficient clearance to drill and fasten holes from the outer barrel; similarly, the horizontal crosspiece may present a problem for holes on the stiffener. Once a fastener is installed at the joint between the chord and the bulkhead, the protruding head and collar may limit future access to drill and fasten the outer barrel.

The Hi-Lok requirement also presents a problem for automation. Automated collar threading technology is in development but not currently available. Successful automated fastener installation at these joints requires technology maturation or a combination of design, material, and fastener changes that address the clamp-up needs of the sealant.

4.1.4 Forward Bulkhead

The forward bulkhead, like the aft bulkhead, provides radial stiffness and can be assembled from elements constructed of titanium [5, 22, 25]. It also stabilizes the lipskin which might otherwise bend and flex. The forward bulkhead is attached directly to the aluminum lipskin on the inner edge by the inner barrel and to the outer edge via a titanium outer angle. Figure 4.6 shows a cross section of the forward bulkhead, lipskin, and forward outer angle. The tolerances of the various components, and the manner of assembly, may lead to small gaps between the forward bulkhead assembly and the lipskin. These gaps can be closed, or pulled up, during fastener installation. A maximum allowable gap is defined to prevent deformation, waviness, and accompanying stress impacts. The reverse D-shape formed by the lipskin and the forward bulkhead assembly creates a channel or duct for hot air from the engine. When circulated, the hot air warms the lipskin which prevents ice from forming on the exterior surface. A high temperature sealant is applied to all interfaces that border the engine anti-ice duct. Holes that pierce the lipskin are countersunk from the outside to maintain fastener flushness in the airstream and reduce drag. Sealant is applied to the these fasteners to protect against moisture penetration.

Automation Considerations

The shape of the lipskin presents a challenge for automated assembly. End effectors are typically too large to fit in the space. The exterior fastener flushness requirement means that drilling and fastening occurs from outside the lipskin but clamp-up for one-up assembly (see Section 3.2) must be provided on the backside, or interior, of the lipskin. C-style end

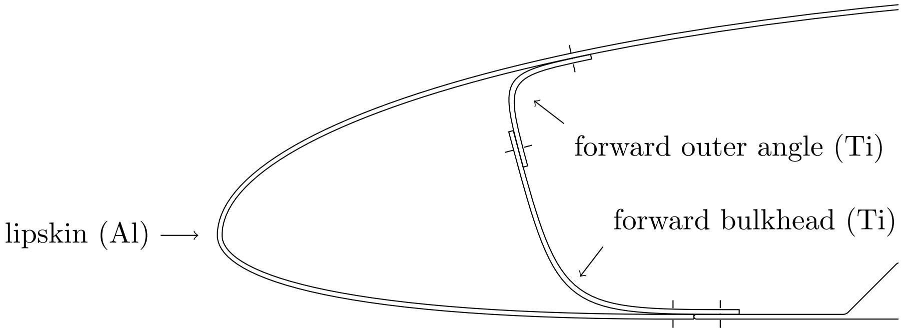

Figure 4.6: Cross section of forward bulkhead, lipskin, and forward outer angle

effectors with sufficient depth may access the joints; this custom solution, however, requires additional design time and significant cost.

The sealant and threaded fastener considerations are the same as for the aft bulkhead (see Section 4.1.3). Exterior fasteners are sealed to prevent moisture penetration and material interfaces receive high temperature sealants. Automated sealant application technology is not sufficiently mature, however, and must be completed manually. Furthermore, the sealants require clamp-up which necessitates threaded fasteners such as Hi-Loks. Robust automated solutions for threaded collar attachment do not currently exist either.

If gap pull-up is a possibility and a maximum allowable gap is defined, automated solutions must be able to measure the gap. This further complicates existing needs for end effectors because vision systems are usually mounted on the drill side. Gap and pull-up requirements necessitate a vision or sensor system on the backside in addition to the collar threading capability already mentioned.

4.1.5 Inner Barrel to Lipskin Join

The inner circumference of the lipskin is located end-to-end with the inner barrel at the forward edge. The lower web of the forward bulkhead attaches to the lipskin and to the barrel. Figure 4.7 shows a cross section of the lipskin, forward bulkhead, and inner barrel. The variability in the thickness of the composite would require the use of shims in a traditional, non-automated assembly operation. The automated approach utilizes matched, or custom, machining to eliminate time-consuming shim fabrication and installation. Matched machining requires a high resolution surface scan of the lipskin and inner barrel at the areas where they interface. The inner barrel is then machined to match the lipskin. After machining, the two surfaces are mated (very tightly) and flush blind fasteners are installed.

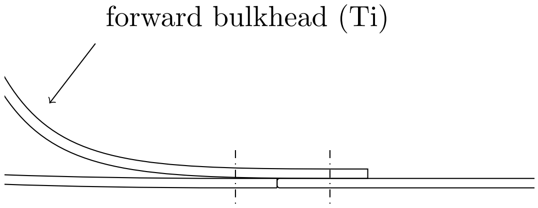

Figure 4.7: Cross section of inner barrel to lipskin join

Automation Considerations

Similar to installation of the forward bulkhead, the inner barrel to lipskin join presents a challenge for automation because of the shape and size of the space relative to typical robotic end effectors. Whereas the forward bulkhead installation to the lipskin can utilize a C-style end effector to reach around the inner edge of the lipskin, the inner barrel blocks this access point at this stage in the assembly process. Possible solutions are to use two separate robots—one on the inside and the other on the outside—or to use blind fasteners with less clamping force.

4.1.6 Outer Barrel Install

The final piece of the nacelle inlet assembly is the attachment of the outer barrel. The aluminum outer barrel is installed between the forward and aft outer chords. Figure 4.8 shows a cross section of the outer barrel, the forward outer chord, and the aft outer chord. Sealant is applied to the interfaces between the outer barrel and the chords to protect against moisture penetration. The aft outer chord is installed as part of the aft bulkhead assembly (see Section 4.1.3) and the forward outer chord is installed as part of the forward bulkhead assembly but is described here. The forward outer chord must be spliced, sealed, and fastened to the edge of the one-piece lipskin.

The outer barrel is built up from two semi-circular halves and must be spliced together. Since the installation of the outer barrel closes out all interior access to the inlet, blind fasteners are used to attach the barrel to the outer chords. The clamp-up requirements for one-up assembly (see Section 3.2) are met by existing fasteners in adjacent holes. These flush fasteners are sealed to protect against moisture penetration.

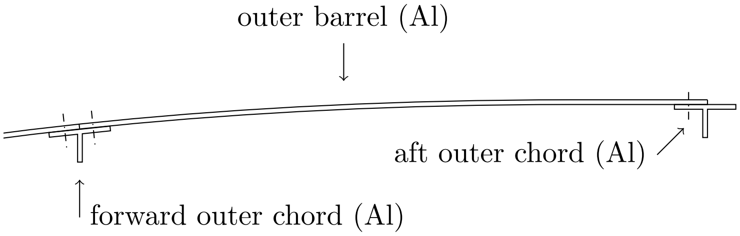

Figure 4.8: Cross section of outer barrel, forward and aft outer chords

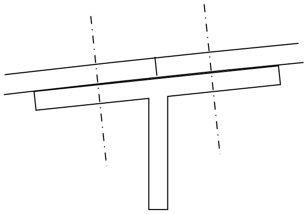

Figure 4.9: End effector access issue on closed angle T-chord

Automation Considerations

The exterior contour of the lipskin and the extrusion design of the forward outer chord result in a closed, or acute, angle. Figure 4.9 shows a close-up of the forward outer chord and the closed angle. Even a relatively small angle presents a problem because the automation must provide back-side clamp-up and the foot of the end effector may be wider than the space available or it may collide with the vertical stiffener. The most straightforward solution would be to make the stiffener perpendicular to the cross piece but this may also impact the ability of the chord to prevent radial flexing of the lipskin at this joint.

4.2 Proposals for Robotic Assembly and Integration

Robotic automation in the aircraft industry has been attempted at various times with mixed results [16, 33]. Unlike industries where robotic automation is thriving, the aircraft industry has relatively low production volumes. Fortunately, the extensive adoption of robots in other industries has increased their reliability and efficiency while reducing cost. Although there are differences in the specific needs and applications of robotics in aircraft assembly, the experience of established robotics systems integrators may overcome some of the implementation challenges previously experienced in the industry.

A discussion of the proposal evaluation and selection process is relevant because organizational procedures influence technical decisions. These activities often result in compromises between technical ideals and business realities. Three robotics systems integrators responded to a Request for Proposal (RFP) for a turnkey solution. The proposals were preceded by a funded engineering development period in which bidders developed and refined ideas, approaches, and concepts specifically tailored to the program.

4.2.1 Technical Evaluation

Various approaches, tools, and methodologies exist to make technology decisions and to evaluate proposals. Research on the adoption of manufacturing technology and automation suggests that many decisions and proposal evaluations continue to involve a great deal of subjectivity [18]. Efforts to reduce this bias and subjectivity and to incorporate more rigorous evaluation criteria have led to studies that focus on technology maturity and the evaluation process. Frackleton uses Technology Readiness Levels (TRL[‡]) to assign risk distributions that are incorporated into the decision process [11]. Rothman discusses the use of the Analytic Hierarchy Process (AHP)—similar in some ways to real options analysis which is derived from financial instruments known as options—to narrow the field of options by making pairwise comparisons[§] using both subjective and objective criteria [24].

Despite this research, industry habits are difficult to change and teams tend to maintain the status quo. A typical approach used to make technology decisions is the decision matrix. A decision matrix involves a list of criteria against which an evaluation is made. Individuals assign scores to each criterion and scores are aggregated to determine an overall score. This score may be used to select a winner or to compare against a threshold value that triggers a decision to move forward. Individual criterion may be weighted to reflect the importance of one item relative to another. These criteria may optionally be assigned to categories, aggregated, and weighted again. Regardless of the depth of organization in the matrix or the number of weights that apply to a certain criterion, the ultimate result is a single effective weight (usually the product of all parent weights). Table 4.1 shows an example of the structure of a typical evaluation matrix. A sample of the actual criteria used in the evaluation of proposals for the engine nacelle inlet are listed in Appendix B. The raw score

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[‡] Technology readiness levels describe the maturity of technologies on a scale of 1–9. The characterization of each level is described in greater detail in Appendix A.1.

[§] The pairwise comparisons used in the Analytic Hierarchy Process are described in more detail in Appendix A.2.

		Weight	Score
Category A			
	Criteria A.1	$w_{A.1}$	$c_{A.1}$
	Criteria A.2	$w_{A.2}$	$c_{A.2}$
	$\vdots$	$\vdots$	$\vdots$
	Criteria A.n	$w_{A.n}$	$c_{A.n}$
Category B			
	Criteria B.1	$w_{B.1}$	$c_{B.1}$
	Criteria B.2	$w_{B.2}$	$c_{B.2}$
	$\vdots$	$\vdots$	$\vdots$
	Criteria B.m	$w_{B.m}$	$c_{B.m}$
$\vdots$			
Category Z			
Raw Total			$\sum_i w_i c_i$

Table 4.1: Structure of typical decision matrix

is calculated by Equation 4.1.

$$\frac{\sum_i w_i c_i}{\sum_i w_i} \tag{4.1}$$

It is also fairly common to normalize the resultant scores against the maximum possible score as a percentage (Equation 4.2). A variation on this approach (especially for competing bids or proposals) is to normalize the scores against the maximum points received rather than the maximum possible (Equation 4.3). This can be particularly important when the scores in different categories are assigned by different individuals, groups, or teams and the average score in one category is higher or lower than that in another category. Without normalizing by maximum points received, the category with a lower average score has a lower effective impact on the final score than the category with a higher average score.

$$\frac{\sum_i w_i c_i}{\sum_i w_i c_{i,max}} \tag{4.2}$$

$$\frac{\sum_i w_i c_i}{max(c_i) \sum_i w_i} \tag{4.3}$$

The cost to purchase or implement technology or automation is of significant importance. Two major approaches to evaluating cost are presented here. The first, or baseline, approach incorporates cost into the decision matrix as either a single criterion or as a category of criteria. The second approach measures the value of the proposal by dividing the technical score by the cost. Value is here defined as performance per unit cost.

A decision matrix was used to evaluate robotic automation proposals in this instance. Cost data was evaluated independently of the technical data and the scores were later merged. In an effort to reduce bias, the technical evaluation team had no visibility into the category and criteria weights nor into the proposed costs associated with each proposal. This was done to eliminate the chance of assigning scores that satisfy preferred weighted outcomes.

The results of the evaluation are summarized in Figure 4.10. The sum of technical and cost scores (the baseline) yield a 4% margin between C (high) and B (low). Dividing the technical score by the cost, however, yields a 7% margin but between A (high) and C (low). Proposal A provides a robust solution: the baseline approach yields a second-place score that is 1.5% lower than the first-place score; the value approach yields a first-place score that is 5% higher than the second-place score. This proposal is strong using both approaches. Proposal B is consistent; both approaches yield similar, second-place scores. Proposal C may be considered the most risky or uncertain: the baseline approach yields a first-place score that is 1.5% above the second-place score but the value approach yields a third-place score that is 7% below the first-place score. This proposal is strong using one scoring approach but weak using the other. Selecting Proposal A results in the highest value and accepts a 1.5% lower baseline score while eliminating the possibility of a 7% loss in value associated with Proposal C.

4.2.2 Financial Justification

The capital investment required to implement a robotic assembly line is not insignificant. The initial investment is offset, however, by both recurring and non-recurring savings. Automated assembly reduces manual touch time and the need for manual tools. It also has the potential to reduce the quantity of assembly jigs, drill jigs, holding fixtures, and certain types of material handling equipment. A successful and efficient automated assembly line improves quality by reducing defects through reliable task repetition. Automated task times are less than manual task times and, when working properly, do not need breaks or periods of rest. When aggregated across the entire build and assembly time, the semi-automated inlet assembly reduces manual touch time by 70%. This drastically improves production capacity and reduces work-in-progress (WIP) inventory. A manual assembly process would require multiple parallel production lines—with an increase in parts, personnel, and equipment—to deliver at the same rate as an automated line with a faster cycle time.

Figure 4.11 shows the first 50 months of manual touch time savings from automation by month of production. The shape of the graph (the declining jagged edges) represents the interaction between the decreasing experience curve (see Figure 3.3) and the increasing rate of production (see Figure 4.2). Specifically, it is the sum of the learning curve for each unit aggregated by month. Other considerations for savings include the reduced factory floorspace and fewer assembly jigs, drill jigs, holding fixtures, and manual tools.

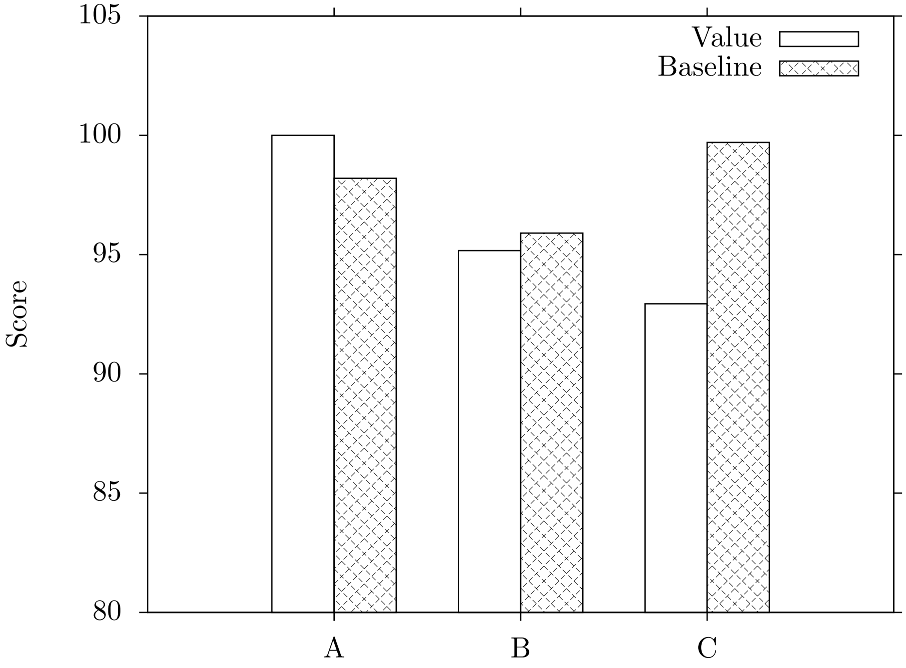

Figure 4.10: Evaluation scoring summary

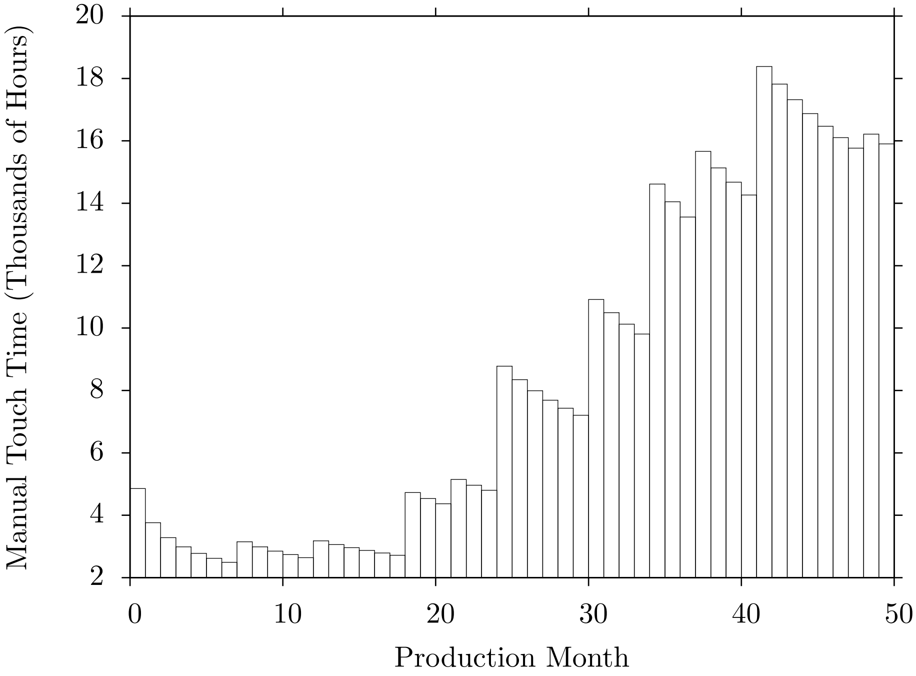

Figure 4.11: Manual touch time savings from automation

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{4.4}$$

The present value savings of the reduction in manual touch time can be calculated using the burdened labor rate. The net present value (NPV) gives the current, or present, value of future cash flows. NPV is given by Equation 4.4 where t is time, CF_t is the cash flow at time t, and r is the discount rate, or cost of money. This method is used to assess the value of investments and expenses that involve future cash flows of differing amounts at various times. It works by adjusting, or discounting, all cash flows to an equivalent value at a fixed point in time, usually the present. Near-term cash flows are more impactful than distant cash flows of the same value. For the engine nacelle inlet in question, the NPV of a robotic, semi-automated assembly line is approximately $250M as compared to a fully manual production line over the life of the program.

Summary

Production of engine nacelle inlets for high-rate aircraft programs presents an opportunity to implement robotic automation. The achievable level of automation is dependent on the technical capabilities of robotic end effectors performing tasks unique to the aircraft industry. The achievable level of automation in this case represents a 70% reduction in manual touch time. The most significant barriers to more extensive automation are physical access limitations, the application of sealant, and the installation of threaded collars on fasteners. Especially for the inlet—which is smaller than many other aircraft components—physical space limitations prevent end effector access. Robust technologies for automated sealant application and threaded collar attachment do not currently exist but are under development. These barriers limit the level of automation, require the design and development of custom end effectors, and ultimately increase cost. Even so, the present value savings of this semi-automated assembly line is approximately $250M.

Schedule, business considerations, and supplier management pressures impact the decision making process and the ultimate value of the implemented system. It should be noted and re-emphasized that this example provides a single data point on a curve. Data points from other aircraft programs, airframers, or robotics vendors may lie on different curves and the curves may change over time as do labor, robotics, and the aircraft market. This demonstrates the difficulty in truly reaching an optimal level of automation.

Chapter 5

Conclusion

Manual fabrication and assembly of aircraft and their components has resulted in a great degree of variability and has historically limited production throughput. Increasing production rates of popular commercial aircraft models and decreasing costs of industrial robotic systems are making automated aircraft assembly more attractive and more practical. The implementation of automated robotic systems has the potential to significantly reduce cost while decreasing defects and increasing throughput. These improvements enable greater flexibility to address changes in the competitive market. The key, however, lies in determining the appropriate level of automation. Determining the appropriate, or optimal, level of automation is a difficult, if not impossible, task. This is particularly true in practice, where a multitude of factors converge and complicate the decision and implementation process. The cost of automation is dependent on these factors, many of which do not have easily-defined relationships with the level of automation. The impact of these factors may differ significantly by aircraft model, geographic region, or robotics integrator, among others. The amount of time and money required to iterate on these factors makes a heuristic approach much more desirable.

Determining a suitable level of automation requires an understanding of current aircraft design, fabrication, and assembly methods. It further requires familiarity with the current capabilities of robotics and end effector technology. Aircraft assembly methods drive the development of automated capabilities beyond that which is used in other industries. Of particular note is the tight tolerance required for many aircraft assembly operations. In turn, the operational improvements afforded by robotic automation motivate manufacturers to make changes in the aircraft design and build plan that accommodate automation. Although the true optimal level of automation may be difficult to identify, significant cost savings can be achieved nonetheless. Individual task time savings of 60–85% combine in the aggregate to reduce total touch time in one case by 30% for a level of automation that reduces manual touch time by 70%. Additional technology development, coupled with aircraft design and build plan changes, has the potential to increase the achievable level of automation, reduce touch time further, and decrease costs. The present value savings of a semi-automated assembly for a particular engine nacelle inlet is estimated at \$250M. This serves as an important data point in future considerations for implementing reconfigurable robotic automation in other aircraft assembly operations.

5.1 Recommendations

A consistent strategy and approach is needed to address the challenges of robotic systems in aircraft assembly. More than just an edict to increase the number of robots or decrease manual touch time, a successful plan addresses both the decision-making process and the technical underpinnings that make it possible.

The foregoing case study identified several approaches to evaluate new or maturing technologies. The exact method is less important than some of the key ingredients. Value, or performance per unit cost, is recognized as a desirable characteristic for almost any purchase decision. Traditional means of evaluation, however, may not consider value in this form, opting instead to incorporate cost by assigning a score and a weight in a decision matrix. At the very least, value should be considered side by side with other scoring and evaluation mechanisms in order to make informed decisions that provide robust solutions in the face of uncertainty.

Planning for and accommodating automation early in the design cycle prevents costly redesign or assembly plan compromises in the future. Successful planning for automation necessitates knowledge of standard robotics and end effector capabilities. The key learnings from this case study are summarized here. First, physical space constraints may limit end effector access. Areas of high curvature, such as wing or inlet leading edges, are of particular concern. These areas may make automation impossible and artificially constrain the level of automation. Second, small component features may limit end effector nosepiece access. Adjacent parts and features that do not hinder manual assembly may inhibit automated assembly. Third, threaded bolts and collars must be used with caution. Wherever possible, automatic threading of collars should be avoided unless new technology is developed. This simplifies end effector complexity and reduces cost. Where lock bolts or Hi-Loks are necessary, reliable collar-threading end effectors must be developed and tested. Meanwhile, these operations cannot be automated. Finally, material selection impacts the use of sealants on fay surfaces and edges. Although this cannot generally be avoided, it must be considered as a barrier to a streamlined automated process.

5.2 Future Research

There is tremendous opportunity for continued research that impacts automated assembly of aircraft components. This research identified a single data point on the level-of-automation curve; the cost of automation is not well understood and further research is needed to determine the sensitivity of the cost to changes in the statement of work. Of particular interest is material movement and the automation of sealant operations. As additional tasks (the last mile) are automated, cost is expected to rise sharply. Understanding the cost of a "lights-out" factory would be a valuable reference.

This research concluded with the selection of a robotics vendor and a contract award. As detailed design progresses and as physical installation, validation, and production begin, design issues will likely present additional challenges to automation. These challenges have an associated cost. A better understanding of originally-unanticipated costs will better inform future financial justifications.

Another area for potential research is the impact of favorable and innovative contracting terms. Third-party robotics integrators, familiar with the automotive industry, are accustomed to brisk ramp-ups and shorter support life-cycles. Special consideration is necessary to identify opportunities that align incentives. Once these incentives have been aligned in principle, the behavior of the parties over time will demonstrate the true value of such arrangements.

The implementation of robotic automation in aircraft assembly is maturing and there is great opportunity to further understand its impacts. The successful automation of 70% of the manual touch time for an engine nacelle inlet suggests there is great untapped potential for robotic automation in other aircraft assemblies.

Appendix A

Evaluation Support Tools

A.1 Technology Readiness Levels[*]

TRL 1 *Basic principles observed and reported.* This is the lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.

TRL 2 *Technology concept and/or application formulated.* Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.

TRL 3 *Analytical and experimental critical function and/or characteristic proof of concept.* Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

TRL 4 *Component and/or breadboard validation in laboratory environment.* Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include integration of ad hoc hardware in the laboratory.

TRL 5 *Component and/or breadboard validation in relevant environment.* Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include high-fidelity laboratory integration of components.

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[*] Courtesy NASA, DoD, Frackleton [11]

TRL 6 *System/subsystem model or prototype demonstration in a relevant environment.* Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.

TRL 7 *System prototype demonstration in an operational environment.* Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g in an aircraft, in a vehicle, in space).

TRL 8 *Actual system completed and qualified through test and demonstration.* Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system to determine if it meets design specifications.

TRL 9 *Actual system proven through successful mission operations.* Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.

A.2 Analytic Hierarchy Process Pairwise Comparisons[†]

Importance	Definition	Explanation
1	Equal	Two elements contribute equally to the objective
3	Moderate	Experience and judgment moderately favor one element over another
5	Strong	Experience and judgment strongly favor one element over another
7	Very Strong	One element is strongly favored over another; its dominance is demonstrated in practice
9	Extreme	The evidence favoring one element over another is of the highest possible order of affirmation

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[†] Courtesy Rothman [24]

Appendix B

Sample Evaluation Criteria

Description	Raw Score (1–5)
General	
Past performance	
Safety & ergonomics	
Technical Capability	
Risk assessment & management	
Robot accuracy	
Control system	
Drill & fill	
Material handling	
Capacity/Process Flow	
OEE: Availability	
OEE: Performance	
OEE: Quality	
Utilization	
Schedule	
Installation & startup	
Impact of long-lead items	
Rate ramp-up	
Ease of Use	
System usability	
Training, documentation, & warranty	
Tooling ease of use	
Maintenance & troubleshooting ease	
Post-installation service plan & support	

References

[1] Airbus. Orders & deliveries.
`http://www.airbus.com/company/market/orders-deliveries`, October 2013.

[2] E. Anderson. Additive manufacturing in China: Aviation and aerospace applications. Institute on Global Conflict and Cooperation, May 2013.

[3] A.A. Baker, S. Dutton, and D. Kelly. *Composite materials for aircraft structures.* AIAA education series. American Institute of Aeronautics and Astronautics, Reston, VA, 2004.

[4] D. Banis, J.A. Marceau, and M. Mohaghegh. Design for corrosion control. *Aero*, 1999.

[5] A. Binks, N.J. James, and M.J. Layland. Inlet section of an aircraft engine nacelle, September 18 2012. US Patent 8,267,642.

[6] The Boeing Company. Boeing design manual: Fastener selection, holes, edge margins and spacings. Unpublished, 1999.

[7] The Boeing Company. Boeing 787 Dreamliner provides new solutions for airlines, passengers.
`http://www.boeing.com/boeing/commercial/787family/programfacts.page`, October 2013.

[8] The Boeing Company. Orders and deliveries.
`http://active.boeing.com/commercial/orders/index.cfm`, October 2013.

[9] Federal Aviation Administration. *Aviation Maintenance Technician Handbook*, 2008.

[10] Federal Aviation Administration. FAA aerospace forecast fiscal years 2013–2033.
`http://www.faa.gov/about/office_org/headquarters_offices/apl/aviation_forecasts/aerospace_forecasts/2013-2033/media/2013_Forecast.pdf`, 2013.

[11] C. Frackleton. Technology maturity analysis for assessing capacity and schedule risk of future automation projects. Master's thesis, Massachusetts Institute of Technology, to appear June 2014.

[12] I. Gorlach and O. Wessel. Optimal level of automation in the automotive industry. *Engineering Letters*, 16(1):141–149, 2008.

[13] J. Herrera. Evaluation of control systems for automated wing manufacturing. Master's thesis, Massachusetts Institute of Technology, June 2013.

[14] B.J. Hogan. Automation speeds A380 wing assembly. *Manufacturing Engineering*, 134(3):121–131, 2005.

[15] G. Jayaprakash, K. Sivakumar, and M. Thilak. A numerical study on effect of temperature and inertia on tolerance design of mechanical assembly. *Engineering Computations*, 29(7):722, 2012.

[16] N. Jayaweera and P. Webb. Automated assembly of fuselage skin panels. *Assembly Automation*, 27(4):343, 2007.

[17] N. Jayaweera and P. Webb. Metrology-assisted robotic processing of aerospace applications. *International Journal of Computer Integrated Manufacturing*, 23(3):283 – 296, 2010.

[18] V. Lindström and M. Winroth. Aligning manufacturing strategy and levels of automation: A case study. *Journal of Engineering and Technology Management*, 27:148–159, 2010.

[19] B. MacIsaac and R. Langton. *Gas Turbine Propulsion Systems.* Aerospace Series. Wiley, 2011.

[20] A.P. McAfee. On the appropriate level of automation for advanced structural composites manufacturing for commercial aerospace applications. Master's thesis, Massachusetts Institute of Technology, 1990.

[21] D.A. McCarville. *Evolution of and projections for automated composite material placement equipment in the aerospace industry.* PhD thesis, Walden University, 2009.

[22] A. Porte. Air intake structure for aircraft engine, March 24 2009. US Patent 7,506,838.

[23] K.V. Ramana and P.V.M. Rao. Automated manufacturability evaluation system for sheet metal components in mass production. *International Journal of Production Research*, 43(18):3889–3913, 2005.

[24] C. Rothman. Objective assessment of manufacturing technology investments. Master's thesis, Massachusetts Institute of Technology, June 2012.

[25] J.D. Shutrump. Aircraft engine inlet having zone of deformation, May 25 2010. US Patent 7,721,525.

[26] T. Sisco. Achieving “one up assembly” by reduction of interface burr height in aluminum, graphite, and advanced titanium/graphite hybrid (TiGr) material. In *SAE Aerospace Manufacturing Technology Conference and Exhibition - 2003 Aerospace Congress and Exhibition*. SAE International, September 2003.

[27] J. Stein. Tool selection and kitting: Technical and organizational issues. Master’s thesis, Massachusetts Institute of Technology, June 2013.

[28] J.M. Stewart. Effects of stack-up, hole diameter, and backing material on titanium burr height in the drilling of multilayer stacks of composite and titanium. Master’s thesis, University of Washington, 2007.

[29] P. Waurzyniak. Modular automation for the aerospace industry. *Mechanical Engineering*, 136(3):81–93, 2006.

[30] P. Waurzyniak. Making smarter automation purchase decisions. *Manufacturing Engineering*, 145(6):45–53, 2010.

[31] P. Waurzyniak. Automating aerospace processes. *Manufacturing Engineering*, 146(3):67–77, 2011.

[32] P. Waurzyniak. Aerospace automation picks up the pace. *Manufacturing Engineering*, 150(3):55–62, 2013.

[33] P. Webb, S. Eastwood, N. Jayaweera, and Y. Chen. Automated aerostructure assembly. *Industrial Robot—An International Journal*, 32(5):383–387, 2005.

[34] D.E. Whitney. Real robots do need jigs. *Harvard Business Review*, 64(3):110–116, 1986.

[35] T.P. Wright. Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences (Institute of the Aeronautical Sciences)*, 3(4):122–128, 1936.

[36] B. Wyse. 737: Meeting market demand. Paris Air Show 2013 Press Briefing. Referenced at: `http://leehamnews.com/2013/06/14/`, presented May 2013.