High Volume Automated Spar Assembly Line (SAL)

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Rick Calawa
Electroimpact Inc.

Gavin Smith
Boeing Co

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Abstract

The decision to replace a successful automated production system at the heart of a high volume aircraft factory does not come easily. A point is reached when upgrades and retrofits are insufficient to meet increasing capacity demands and additional floor space is simply unavailable. The goals of this project were to increase production volume, reduce floor space usage, improve the build process, and smooth factory flow without disrupting today's manufacturing. Two decades of lessons learned were leveraged along with advancements in the aircraft assembly industry, modern machine control technologies, and maturing safety standards to justify the risk and expense of a ground-up redesign. This paper will describe how an automated wing spar fastening system that has performed well for 20 years is analyzed and ultimately replaced without disturbing the high manufacturing rate of a single aisle commercial aircraft program.

Introduction

The Boeing Renton Factory in Renton WA is a busy place. For decades, the 737 narrow-body commercial airliner has been built there. Manufacturing equipment and processes have changed dramatically over those years. Originally and for many years, mechanics drilled and bolted wing spars together by hand. In 1994, the company installed the first four computer controlled ASAT3 wing spar assembly machines. There would eventually be 10 of these enormous gantries. They bolted together numerous parts to produce the four wing spars for every airplane that rolled out of the factory. The automation produced high quality assemblies. However, as market pressure drove rate increases equipment engineers foresaw that these aging machines would soon be unable to supply the needs of the wing line.

Transitioning from a proven automated assembly platform that produces a given assembly in a multi-piece flow layout to a takt time based flow line that produces the same part in less than a quarter of that time is a complicated problem. It is not just a matter of buying a faster fastening machine, although this can help. It is a study of the build process and an exercise of the lean principles. As is typical, relatively good data was available from the automated equipment, but analyzing it showed that machine run time was only a fraction of the overall build time. Numerous manual interactions required frequent machine stops. All maintenance required production stops or late night and weekend work. Build times varied widely.

The wish list for a new spar production system was ambitious:

- No large production disruptions.
- Increase production capacity.
  - Create a single flow line and reduce buffer requirements by matching the takt time of the wing lines.
  - Reduce manual interactions and planned machine stops.
  - Separate manual and automated work.
- Reduce floor space requirements.
- Use mobile machines to facilitate periodic maintenance and high availability. Move machines without relying on the overhead crane.
- Enable additional process improvements.
- Design in workplace safety meeting or exceeding international standards.

Minimize Disruptions

In order to obtain accuracies needed for this type of assembly a rigid foundation is required. This level of concrete work is costly and disruptive, especially inside of a crowded high-rate factory that is in full operation. For these reasons, the team chose to reuse the primary slab of two of the existing ASAT3 foundations. While this choice saved tremendous expense of time and money and greatly reduced production impacts, it also placed severe restrictions on the new cell boundaries and factory floor layout, which would affect nearly every aspect of the project.

Other decisions intended to minimize impacts to the surrounding factory include designing major structure to respect overhead crane height and load limits and detailed planning of every crane pick. Despite the size and variety of steelwork, no mobile cranes were used during the entire installation. All lifts with the factory cranes were prepared in advance to reduce the time required and increase safety. Major components were delivered just in time, picked from the truck and set directly in final position. Staging areas were limited and removed from the immediate high-density area around the production cells. Machines were shipped fully assembled. It took less than 40 minutes from the time the truck rolled into the factory until the machine was set in place and released from the factory crane. Of that time, only a small portion was the lift itself. This process was so efficient that it was allowed during a specific time at midday, rather than being relegated to nights or weekends.

Plan the New Flow Line

The decision to reuse the existing foundation limits the options for laying out the production system. In making this decision, the overall layout and the needs of the final production line must be considered. A build plan was created which separated manual work from automation. A material handling plan was created to move these long awkward assemblies through the build phases. Contingencies and possible future automation were factored in.

Minimize load and Unload Times

The previous automation plan comingled manual and automated work, reducing the overall effectiveness of the automation. Loose components were wheeled into the automation cell in shipping carts. There they were cleaned, inspected and sealant was applied. Finally, five machine operators loaded the components into the assembly jig by hand. During this entire time, the automated equipment sat idle. During the actual part load, four other machines were stopped so that their operators could help wrestle the parts into the jig. For technical reasons, not all of the required parts could be loaded at the start; so much of this process was repeated part way through the assembly process. Again, the machine sat idle until the manual work was done.

Part load and unload were targeted for overhaul in the new system. The plan included a staging position prior to each automation cell. Here, components are removed from their shipping carts using a purpose-built overhead system and fitted to custom loading tools. The parts can be cleaned and inspected while in the loading tool. Sealant is applied and the parts are ready for the initial load. All of this manual work is done while the machines are operating in the adjacent automation cell. When fastening is complete, the previous spar is unloaded from the automation cell using a custom unload tool. The loading tool is then rolled in and the component parts are transferred to the assembly jig. Both the load and unload tools are large. A small electric tug is used to move each tool in and out of the cell. The motion of the carts is guided by pins, which rise up from the floor. Once in place in the assembly cell, a servo motor driven system grabs hold of the tool and moves it accurately into place to transfer parts to or from the assembly jig. Each operation requires no more than two people. The entire unload and reload process is greatly reduced. This is both a significant time savings and a safety improvement over the previous system.

Eliminate Planned Stops - Automated Tool Change

Fastening machines typically require end tooling specific to each diameter and type of fastener being installed. Aircraft structure is highly optimized for strength and weight, often using a broad range of fasteners in a single assembly. This leads to many tool changes. In this case, specific technical requirements of the assembly also necessitate a two-stage build. As mentioned above, parts are loaded into the assembly jig and fastened and then more parts are loaded to complete the assembly. This second automation pass repeats many of the tool changes done in the first pass. In all, the legacy system needed up to 18 tool changes to build a spar.

Tool change on the previously existing system was a manual operation. While a two-minute tool change could be demonstrated in testing, time studies showed that it commonly took between 5 and 15 minutes in production. These planned system stops also invite additional distractions to the operator. With 10 to 18 tool changes needed over the course of a 24 hour build, up to 15% of the day could be spent in changing tools. Production loss could be worse after additional distractions are added on.

ASAT3 machines have an operator station attached to the gantry. The operator rides along and not only acts as tool changer, but also forms an important part of the machine safety system. If anyone approaches, the operator stops the machine. Even a brief conversation with a supervisor requires a production stop. This type of loss creates two problems in a takt time based production system. The first issue is a drastic under-utilization of expensive equipment. Second, the variability makes scheduling and predicting completion times extremely difficult.

In addition to saving time, automated tool change provides other benefits to a fastening machine. Manual handling of drills leads to accidental breakage. An automated drill change removes this issue and leads to longer effective drill life. Automatic tool change also enables more reliable life tracking of automatically changed components. Wear items such as bolt-feed fingers can be serialized and tracked automatically, facilitating scheduled maintenance.

Figure 1. Yellow Robot Arms Change Process Tooling

In order to reduce production time, get consistent results, and obtain the other benefits described above, a fully automated tool change with onboard tool storage was required. A separate technical paper, “Fully Automated Robotic Tool Change” [1] describes the details of this implementation. The technology proved critical to the success of the system as a whole. Two robotic arms were mounted to each machine. The work was divided between them for efficiency. Common tool interfaces were developed for the tools handled by each arm. In all, five tooling elements may be changed: drill bit, hole probe tip, bolt anvil, clamp nose, and collar or nut tool. A complete tool change, including calibrating the new tools, takes approximately 70 seconds.

Meet the Takt Time

Reducing losses due to loading and unloading, manual tool changes, minor unplanned stops and operator distractions greatly shortened the time required to fasten the spar assembly. However, in order to match up with the takt time of the rest of the wing line, more was needed. With available technology, a single machine could simply not install the fasteners fast enough to build the assembly in the available time.

One-up bolt and collar installation is a multiple step process. Despite improvements in clamping, drilling, fastener delivery and collar swaging, the spar geometry and fastener requirements are such that operations still currently require more than 6 seconds per bolt. Time studies determined early on that achieving the desired production rate with a single cell would require two machines operating in concert on each spar assembly. This proposal initially met with skepticism because of the inefficiencies often experienced in such systems when one machine is interfering with the other. Prior to the start of the project, industrial engineers created a virtual simulation of two machines balancing the fastening workload. This formed early estimates of machining time and built confidence in the overall feasibility of the project. The simulation also determined a maximum width for the machines. If the tool point of the inboard machine could get within a certain distance to tool point of the outboard machine, there were minimal conflicts. Finally, engineers conducted shop floors tests using the existing production equipment to explore possible issues with a two-machine build. In the end, the team was convinced that two machines were required per cell and that the assembly process could be efficient.

Implementing a multi-machine cell is challenging. Generally, some form of cell control is needed to supervise the interaction between machines and to monitor or control shared resources such as the assembly jig or cell-wide safety systems. Complex cell controllers distribute work dynamically to the machines in the cell, leveling workload as needed. In this case, a simple cell control scheme was designed to allow each machine to signal the other as to its fastening progress. Although the sequence is designed to avoid machine conflicts, a machine will wait as needed if the other has not yet reached a predefined milestone in the process. Machine to machine and machine to jig anti-collision software protect against dire consequences from loss of synchronization. Simple rules were created to prioritize operations and allow machines to recover automatically from certain conflicts. Dynamic workload leveling was considered but ultimately rejected for one simple reason. There was simply not enough space to realize the benefits of being able quickly to transfer work from one machine to the other. More on this in the next section.

Reduce Floor Space Requirements

The legacy spar machines are enormous. The desire to reuse the existing foundations put hard restrictions on cell size, but fortunately, the original automation cell swept out substantial floor area. That rectangle was then cut in two to create a separate staging position for manual work. In order to obtain the desired part flow through the factory, the remaining area must hold two automation cells. That is two assembly jigs and four fastening machines in less than the space of one of the gantry systems. The desired tool point to tool point dimension was far smaller than could be achieved with two of the old machines. The team had to consider how to reduce the equipment size. The design of the assembly jig was a major factor in machine size. Another factor was bulk fastener feed. Another was the ride-along operator station.

The wing spar is roughly 18m long and 1m chord to chord at the root end. It is held in roughly the same orientation it would have in the aircraft during level flight. A fastening machine running a 2-sided process would then need a little more than 1m of throat depth to reach from above and access the lowest fastener. However, traditional tooling design on the legacy system required a large upper beam over the top of the spar with holding clamps hanging down to support the upper chord. The original machines were large because they had to support a yoke with a throat depth of 2m in order to reach around the upper beam and all the way down to the lowest fastener. The new system uses a “no-top” fixture with upper clamps on posts that reach up from the floor and then drop down out of the way to provide local access for fastening. There is only about 100mm of clearance required for clamps beyond the top of the part. Both old and new machines were designed around the same process loads so decreasing this lever arm drastically lessens the required structure. This change did more to reduce the size of the fastening machines than any other single factor.

Figure 2. ASAT3 - Spar Visible in Center of Jig

Onboard fastener storage was also a major contributor to the size of the existing equipment. The original fastener feed consisted of a large rack of bolt hoppers and vibratory bowls for nuts and collars. This arrangement provides convenience in that fasteners are simply poured from boxes or bags directly into the onboard hoppers or bowls. However, it is an extremely large system. As described above, the spar assembly uses a wide variety of fastener types and diameters. However, in many cases there may be only a small number of any specific fastener. Rather than a general purpose bulk feed style system, a compact kit of fasteners optimized to the specific needs of the assembly was needed.

A high-density system using an array of fastener cartridges was designed. Bolts, collars, and nuts occupy tall, narrow cartridge plates. Each bolt cartridge contains up to 16 tubes. Each tube can hold a single type, diameter, and length of bolt. Several tubes could be allocated for a high quantity bolt. A low quantity bolt might occupy only a single tube. The kit of cartridges is optimized for the work package for a full day of production at the target rate. The paper "Plate Cartridge Compact Flexible Automatic Feed System" [2] describes the new system in detail.

One principle drawback of the cartridge system is the need for offline loading. While the hopper feed system could be directly filled from loose bags of fasteners, the new, kitted system requires an automated machine to load cartridges. This loading equipment is quite similar to the old onboard feed. There is a large rack of hoppers on one side. Each hopper contains one type, diameter, and length of bolt. On the other side, there is a rack of plate cartridges. Each plate cartridge is identified by an RFID tag, which describes the required contents of each tube. The loader machine reads the tag and automatically feeds the required bolts from the hoppers into the cartridge tubes. Cartridges are then grouped into kits and staged near the automation cells. This cartridge system greatly reduces the overall size of the fastening machines, but the requirement for offline loading creates a potential single point of vulnerability for the production line. The offline loading system is discussed in a separate SAE paper [3].

The final decision that enabled a significant size reduction was the removal of the onboard operator station. The previous machines included a ride-along operator platform. While having the operator close to the fastening head is ideal for visibility and process monitoring, it increases the width of the machine, limits machine accelerations and presents significant safety concerns. Industrial robot arms for tool change add a variety of additional hazards for operators in the automation cell. The large safety buffer areas required around the robots increase the effective width of the machines, exacerbating machine-to-machine interferences. For speed, safety, and efficiency, it was imperative to move the main machine operator console outside the boundary of the automation cell.

Figure 3. Remote Operator Station Controlling One Cell

Address Single Point Vulnerability

The previous assembly cells included both dedicated and flexible assembly jigs. A dedicated assembly jig is designed to hold one specific part, for example, the right front spar. In this context, a flexible jig is one designed to hold both the left and right hand of the same part. The flexible jigs of this era added manufacturing options, but they tended to be more complex, more expensive, and less efficient to use due to the time required to switch from one configuration to the other. In all, there were ten machines, eight dedicated jigs and two flexible jigs. This provided three possible locations to assemble each of the four spars. While this left expensive assets underutilized, it meant that any one machine could be stopped without stopping factory output.

A single piece flow line, by definition, makes factory output dependent upon all production equipment in the line and critical support branches. The new production system includes only four cells, each with two machines and one dedicated assembly jig. With the new system, the factory now has only one place where a right front spar can be assembled. Any failure of that cell which jeopardizes takt time effectively delays the output of the entire factory.

Further, the shutdown of either machine in a cell constitutes a complete shutdown of the cell. Because of the space restrictions created by the reuse of existing foundations, it was not possible to create park zones for the machines at either end of the automated cell. Neither inboard nor outboard machines can move far enough out of the way to allow the other machine access to the entire spar. Additionally, because of limited on-machine storage space, the fastener kits for inboard and outboard machines must be optimized for the work planned for each. This means that a breakdown on any one of the eight machines in production quickly begins to influence the entire line.

An automated fastening machine is a complex piece of equipment with many moving parts. As the most complicated single item in the system, the fastening assets represent the single greatest risk to uptime. To address this concern, the machines are designed to be removable. The machine tower sits atop an X axis sled. The bottom of the sled mounts to standard recirculating bearing cars and incorporates the motors, gearboxes, and pinion drives which propel the machine. The top of the sled provides a repeatable quick-locking feature that engages the bottom of the machine tower. One power cable, one signal cable and one pneumatic hose are connected manually from the sled to the machine. With this design, it is possible to remove a machine from service for periodic maintenance or to address an emergent issue. Examples of similar mobile designs can be found in references [4][5][6]. The completed system includes ten machines, eight production sleds and two sleds in a nearby maintenance area.

Two purpose-built wheeled transporters were designed to lift machines off their sleds and move them between the production and maintenance areas. The u-shaped transporters wrap around a machine and lock securely to the tower using four manual hydraulic clamps. Power for lifting is provided by a standard shop airline. A fail-safe ratchet system holds the load in the event of a pneumatic failure. Once raised off the sled, the transporter is toed across the floor by an electric tug. The time to swap machines, from power down of one machine to ready-to-run of the next is approximately 20 minutes, not including driving time between the maintenance area and the production area.

Enable Process Improvements

Designing a new system provides an opportunity to implement small advancements that would be impractical to retrofit. Some of the more significant enhancements include improvements to part holding, referencing, part clamping, temperature compensation and stability of the machine to fixture relationship.

The indexing scheme was modified to remove over-constraints. The original fixture design held the spar chords in such a way that as the chords and web were fastened, allowable manufacturing tolerances in the parts would create an over-constraint in the assembly. While the longitudinal station of the chord indices is similar in both the old and new assembly jigs, the shape of each index and the exact points of contact were changed to remove binding that existed in the original jigs. The new scheme still set the critical dimensions of the assembly, but the finished spar is now much easier to unload.

The legacy system used removable tooling for the primary index feature relating the machine coordinates to the tooling. The new tool design incorporates a permanent reference point. This eliminates the manual work of installing and removing the temporary tool, and it improves accuracy.

An automatic clamping sequence was incorporated for consistency in loading. During the handoff from the portable loading tool to the assembly jig, the jig clamps are closed in a programmed sequence. Previously, clamps had been closed manually without regard to particular ordering. It was found that a multi-step controlled clamping routine reduced gaps between parts prior to fastening. Smaller starting gaps produce lower residual stress in the finished assembly.

The factory environment is not temperature controlled. The previous machines have software compensation for thermal growth of the aluminum aircraft part. However, the temperature sensor is mounted to a test piece assumed to have similar thermal inertia to the spar components. The new assembly jigs incorporate contact temperature probes directly into their structure. The jig controller reads direct measurements of the spar temperature at two locations plus a measurement of the bed temperature. These data are passed to each machine in the cell, where they are used to adjust the location of fasteners and determinant-assembly features.

The original spar machines are gantries. Each leg of the gantry is supported by a machine bed. The spar fixture is a separate structure, connected to the machine only through the foundation. This arrangement led to differential movement due to settling, water table changes, and seasonal changes in temperature. In the new system, one monolithic steel structure supports both spar fixture and machines. This design has improved stability. The tooling details no longer appear to move seasonally with respect to the machines.

Improve Worker Safety

This paper has already described some ways in which worker safety is improved in the new system. Part loading and unloading tools mechanically assist the handling of long, awkward parts. Automatic clamping sequences remove the need for workers' hands close to fixture clamps as they actuate. Remote operator stations move people outside a safety perimeter, away from fast-moving hazards. Automatic presence detection lowers the reliance on human vigilance for safety of others approaching the cell.

The presence of industrial robots in the cell, even used intermittently for tool change, forces the entire cell to comply with robot safety standards.[7] These standards are highly prescriptive. They require a functional safety approach, a detailed risk assessment, a compliance checklist, statistical calculations of system performance level and a written plan for recurring testing. This rigorous design approach affects hardware and software architecture, communication protocols, and human procedures.

The result is a coherent plan for safely performing daily tasks in the cell. The plan addresses full speed production, maintenance and diagnosis, reduced speed program try-out, part load and unload. While it may not seem intuitive that introducing robots to the cell actually improves safety, in the current environment it does force a very thorough procedure to identify, remove and mitigate risk, which might otherwise be cut short.

Summary/Conclusions

To date, the SAL project is succeeding. The system has been meeting performance targets and beating the plan for ramp-up into production. Floor space is reduced by 70%. The preliminary effort to thoroughly scrub the build plan and understand the requirements of the system was an important enabler to this success.

As with any project though, there are compromises that when viewed through the benefits of hindsight may have been better addressed. The project schedule was accelerated in order to maximize return on investment. Because the schedule was so aggressive, the fifth machine was being assembled before the first machine had been significantly tested. This severely limited the ability to correct mistakes or improve the design.

With the system continuing to ramp into production successfully, there is still substantial work to insure the long-term success of the platform. This production cell and the concepts that it is based on represent a substantial shift in mindset of the maintenance community. Setting up and refining the maintenance procedures, supplying and organizing the maintenance areas, obtaining and refining the needed training. These are all things that need to be carefully engineered if the system is still to be viewed as a performance success in 5 or 10 years.

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Contact Information

Rick Calawa
Lead Controls Engineer
Electroimpact, Inc.
rickc@electroimpact.com

Gavin Smith
Equipment Engineer
The Boeing Company
gavin.l.smith@boeing.com

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