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Panel Assembly Line (PAL) for High Production Rates

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Abstract

Developing the most advanced wing panel assembly line for very high production rates required an innovative and integrated solution, relying on the latest technologies in the industry.

Looking back at over five decades of commercial aircraft assembly, a clear and singular vision of a fully integrated solution was defined for the new panel production line. The execution was to be focused on co-developing the automation, tooling, material handling and facilities while limiting the number of parties involved. Using the latest technologies in all these areas also required a development plan, which included pre-qualification at all stages of the system development.

Planning this large scale project included goals not only for the final solution but for the development and implementation stages as well.

The results:

- Design/build philosophy reduced project time and the number of teams involved. This allowed for easier communication and extended development time well into the project.
- All design teams (machine, tooling, automation, controls) collocated and worked together on integration during all stages of development and implementation for the highest level of integration.
- Innovative integration of the tooling and the automated equipment evolved throughout project with the teams working as one group.
- Latest fastening technology using all electric, ball-screw squeeze riveting was developed for high-speed and robust automated fastening.
- Latest mobilization technology was used to make the automated fastening machines interchangeable to reduce MTTR and to enable more PPM activities offline without affecting production.
- More automation was also introduced for tool changing and to the material handling systems for more consistent processing and to reduce operator intervention.
- All systems were developed together for full integration and to enable more safety interlocks and HMI for simplified operation.
- A 30 month schedule for the complete large scale assembly line was maintained to support the new aircraft launch schedule.

The final solution was a coherent, streamlined and efficient assembly line capable of very high aircraft production rates (Figure 1).

Figure 1 PAL, automation cell, Line 4, Position 1 (L4P1)

Introduction

At the conception of the Panel Assembly Line (PAL), goals targeted not only the final solution but the development and implementation as well. A focus on integrating the latest technologies also required planning at every step.

Development and Implementation Goals

During the development and implementation stages, large scale projects suffer from concept divergence and integration challenges when compared to smaller projects. Problems typically exist at the interfaces as the saying goes. With so many subsystems, large scale projects suffer from an abundance of interfaces and staff. Furthermore, incorporating new technologies greatly increases risks to a smooth start-up. Listing developmental and implementation pitfalls for large projects was key to converging on the goals necessary to provide the best solution to realize the original vision while reducing overall project time. Some goals and the associated pitfalls they overcame included:

Integrated Teams: Separating the subsystems into different contracts puts barriers to the flow of the project. By integrating the main technical teams (Tooling, Automation and Material handling), fostered a clearer understanding of the limiting factors or effects of different design decisions that might otherwise be overlooked due to natural separation of responsibilities of each subsystem.

Leadership: Maintaining consistent leadership throughout the project avoids complicating or diluting the original vision and goals. The goal for PAL was to maintain the same leadership throughout the development, implementation and production start-up stages.

Communications: Large scale projects can suffer from communication issues due to an overwhelming number of staff, suppliers and disciplines. New tools needed to be developed to clearly communicate schedule and schedule changes.

Reduce Project Time: Because divergence of goals is exaggerated on lengthy projects, management methods, such as design/build, were required to help reduce the overall project time.

Maximize Development Time: Specific technical solutions might stand on their own merits but may not integrate well or support the overall system if developed independently. Design periods of subassemblies should extend into the build and even into the implementation stages to maximize development and to incorporate changes to the latest possible point in the project.

Mitigate Technical Risk: Reduce the risks of new technologies with concurrent testing programs integrated into the program schedule at the start of the project. Also find ways to avoid risks associated with disassembly of major components for shipping.

Final Solution Goals

The specification for this assembly line was thorough in listing requirements and over-arching goals were also emphasized to suppliers.

Latest Technologies: Incorporate the latest technologies in the areas of Automated Equipment, Tooling and Material handling to increase quality, reduce operator intervention and reduce flow time.

Innovative Tooling: Sleek new tooling, optimized for PAL fastening machine access and cycle time, was required to accommodate new aircraft panels, legacy aircraft panels and all of their variants.

Mobile Machine and Offline MRO: Reduce interruptions to the production line by reducing or removing MTTR.

Semi-Automated Material Handling: Use the fastening machine operators to operate the tooling and material handling systems. Not limited to part damage control, semi-automated material handling reduces required skills and reduces flow time across the entire production process while avoiding dedicated crews.

Increased Safety: Addressing safety not only in each of the project areas, but addressing safety on a complete system level was a requirement.

Once these goals were established, the team selection process was clearer with a good path to realize the project vision.

Development and Implementation

Integrated Teams

Prime supplier selection was based on the design/build capability, expecting expertise on as much of the three sub-systems as possible which included: automated fastening equipment, tooling and material handling. Design/build management was a key to reducing some of the many challenges of this large scale project as well as maximizing development time while minimizing implementation time. A supplier that has multiple disciplines can execute concurrent engineering more naturally. Collocating the teams in the same physical space throughout the project greatly reduced the communication issues typical with separate suppliers. System interfaces were more frequently reviewed and changes were much more closely monitored. Sometimes, challenges in one of the project areas were overcome by making smaller adjustments to other areas. These decisions were based on optimizing potential cost or schedule impacts.

Leadership

Leadership was chosen and required to stay with the program from the start of the design process until the system was in production for several shipsets to ensure that goals and vision were maintained and changes were monitored to reduce divergence. Teams were assigned with only a single layer of management (engineer/project manager) and these teams were co-located during the design and fabrication stages. Only one-for-one contacts were established between customer and supplier.

The opportunity to open communication directly between the leadership from each group was not only recognized but became an important tool as the project reached the point where the three main suppliers would occupy the same space in the construction area. The prime supplier assigned key personnel to oversee individual aspects of the project with the idea that the assigned lead would take ownership and remain with the project through to its conclusion. This required multiyear commitments in some cases but was an important internal goal for meeting the time constraints presented on this program. These commitments helped smooth planning change due to emergent issues.

Communications

Traditional communication or management tools for planning became much too complex for combined detail schedules or too diluted for master schedules.

Constructing the foundation for the assembly line was of particular importance and during the design phase all parties met weekly to detail requirements and verify foundation dimensions and facilities layout. As the project progressed, it became apparent that scheduling interface dates for transitioning control of the construction site was not clearly understood by all teams. To remedy these issues, a simple new tool was developed: the "Integration Exercise". To support this exercise, critical milestones for the project were identified for the main sub-systems: Automated Fastening, Tooling, Material Handling and Foundation (Figure 2).

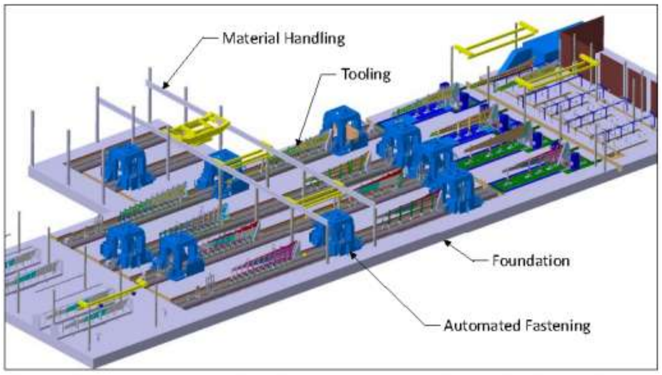

Figure 2 Panel Assembly Line (PAL) Subsystems.

The prime supplier was contracted for the first three subsystems and another supplier was contracted for the foundation. Early in the project, leaders from each area were brought together with the corresponding customer contacts to review the project. The leadership team worked to identify critical dates, however, it became clear that hardware ready dates or foundation ready dates were not enough to plan the project within the required 30 month period. This was because there were multiple zones with varying access needs and the typical finish/start planning was inadequate because sequential planning would have stretched the project out for many more months/years than was required.

Therefore, more attention was paid to understanding need dates and access dates for each stage and in each zone. These dates were often hidden within the different schedules and were far from typical "completion dates". For example, foundation ready dates were not going to be complete in time to meet overall installation times.

All teams met to refine understanding of each step of the installation. Dates were identified for access or semi-access where different teams would overlap. It also became necessary to define the priorities with one team starting while another team was still finishing. Once interface dates were understood and agreed to by all teams, the dates were captured in the tool below and became contractual (Figure 3). Although there were many "minor" dates that could change throughout the project, maintaining these milestone dates would be key to a successful execution and understood by all parties.

VPAL Schedule Integration		EI REVISED Install Sequence & Flows Integrated with Skanska 8/7/13									
		Pos 0		Pos 1		Pos 2		Pos 3		Pos 4	
		Start	Compl	Start	Compl	Start	Compl	Start	Compl	Start	Compl
Maintenance Shed & Machine #1	Machine Install			6/26/14	10/6/14						
	Pour #3				12/13/13						
	Stabilize Foundation			12/13/13	5/14/14						
	Slab on Grade				2/5/14						
	Ready for Crane/Transporter			4/24/14							
	Ready for Bed Install										
	Crane / Transporter Bridge Install			4/24/14	5/21/14						
	Bed Install			5/12/14	6/9/14	1/4/16	1/18/16				
	Floor Install			6/10/14	6/30/14	1/19/16	2/7/16				
	Sled Install			6/9/14	6/25/14	1/19/16	2/2/16				
	Machine Install			6/26/14	10/6/14						
	FAT & Qual			10/7/14	11/25/14						
	Ready for Use			11/26/14							
Line 4 Far East	Lower RH Startup	11/25/14		11/25/14		12/10/14		12/23/14		1/13/15	
	Pour #3				3/7/14						
	Stabilize Foundation										
	Slab on Grade										
	Ready Transport/Monorail Install	7/1/14		5/5/14		5/5/14		9/9/14		9/23/14	
	Transporter Install			5/5/14	6/27/14	5/5/14	6/27/14				
	Monorail Install	7/1/14	7/9/14	5/5/14	6/27/14	5/5/14	6/27/14	9/9/14	10/9/14	9/23/14	11/17/14
	Beds Install (rough in & final align)			7/7/14	8/19/14	8/20/14	9/3/14				
	Floor Install			8/20/14	9/11/14	9/4/14	9/24/14				
	Tooling Install			9/12/14	11/10/14	9/25/14	11/21/14	10/2/14	12/30/14	11/18/14	12/15/14
	Sled/Comp			10/12/14	10/26/14	10/26/14	11/9/14				

Figure 3 Partial view of Integration Exercise document

Once the overall plan was defined, implementing and tracking required great focus and more communication tools for the leadership. In an effort to map out site control areas, the teams agreed on a template to communicate needs in certain zones (Figure 4 and Figure 5). The necessity to establish area control was based on how critical the task was to the whole of the project. It was agreed that the end user would drive these decisions. These changed over the course of the project but the idea was to lay out a frame work as a starting point and maintain the open communication about ongoing tasks required in each area. Using this tool it was possible to complete concurrent work in areas normally subject to sequential tasks. As the foundation came together areas were highlighted and labeled as under the jurisdiction of particular vendors in weekly meetings. Figure 4 and Figure 5 illustrate the control zone layout concept.

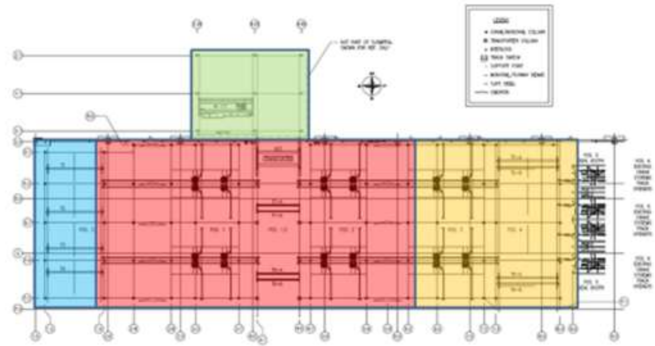

Figure 4 General layout of cell used as template for establishing control zones. Base color indicates general access area only available once the final concrete pour was complete.

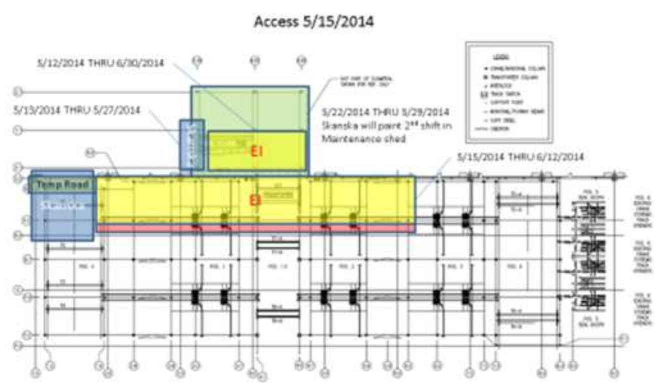

Figure 5 Example of identified control zones. Zones not colored indicated areas under the jurisdiction of concrete contractors.

Reduced Project Time

By using the design/build management method, design completion dates became significantly more flexible. Tent pole items were identified and planning used these items as trigger points. All of the subcomponents or subsystems could "float" in planning around the tent pole items. As mentioned, sequential planning would have increased the overall project schedule significantly. Managing development, fabrication, test and installation as finish/start tasks may have simplified planning but only to increase delivery time of the system. Instead, using the Integration Exercise tool allowed the teams to implement systems in a more just-in-time fashion with design, fabrication, construction, testing and installation occurring concurrently in most cases.

Maximized Development Time

By using the design/build teams, design teams could focus on designing tent-pole items of each subsystem first, then address the other subassemblies well into the fabrication stage and even into the implementation stage (*Figure 6*). This accommodated concurrent engineering of the new aircraft as well as delaying some subsystems designs as late as possible to allow for changes or challenges that surfaced during the progression of the project.

For example, tooling bases were very long lead and so were designed with systematic interfacing that could be determined early. Tooling posts and indexes could be concurrently designed along with the automated fastening head and the new aircraft at a later date without delaying the main tent pole item of the system.

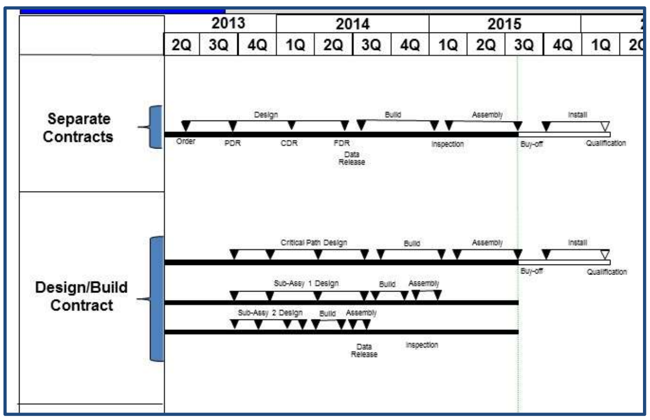

Figure 6 Example master schedule comparison

Risk Mitigation: Fastening Process Test Bench

Utilizing new technologies inherently introduces risks that need to be mitigated as early as possible in order to assure on-time implementation. Table 1 lists several technology risks and the pre-testing efforts used to mitigate them.

Table 1. PAL technology risks and the pre-testing methods used to mitigate them.

TECHNOLOGY RISK	MITIGATION METHOD
Pre-Qualification Drilling & Fastening Process Recipes	Process and Clamp Table Test Bench
Fastener Injector Reliability	Injector Test Bench
Pre-Qualification Clamping Sequences	Integrated System Test
Pre-Qualification Rivet "No-Wink" Software Algorithms and Hardware	Process and Clamp Table Test Bench and Integrated System Test

The PAL test bench (Figure 7) was the primary enabler of pre-qualification efforts. It utilized production fastening heads mounted on a fixed structural frame to allow development and testing prior to the full machine completion. The test bench system was then installed in the customer's factory to allow development to begin for all of the pre-qualification items listed in Table 1.

The test bench was successful in reducing the overall development time as designs were refined and some process parameters were developed in advance of the actual machine ready dates.

Figure 7 PAL test bench includes the operator control, process tools, shuttle table, clamp tables and vacuum system of actual production machine.

As a general rule, a test bench should represent the actual machine it is intended to emulate as closely as possible in order to avoid unanticipated technical problems. Because the test bench did not include the massive positioning axes and structure necessary to move the tool point to all fasteners in a wing panel, it differed significantly from the production machines (Figure 8). Instead of positioning axes and structure, the test bench incorporated only simple structure and a coupon holder with XY positioning capability. Furthermore, PAL test bench did not include a fastener feed system that later proved problematic during rivet qualification.

Without the pre-qualification efforts employed for PAL, however it would have been impossible to implement PAL on schedule. The technology challenges mentioned herein are evidence that problems can arise if pre-qualification methods differ from final machine configuration.

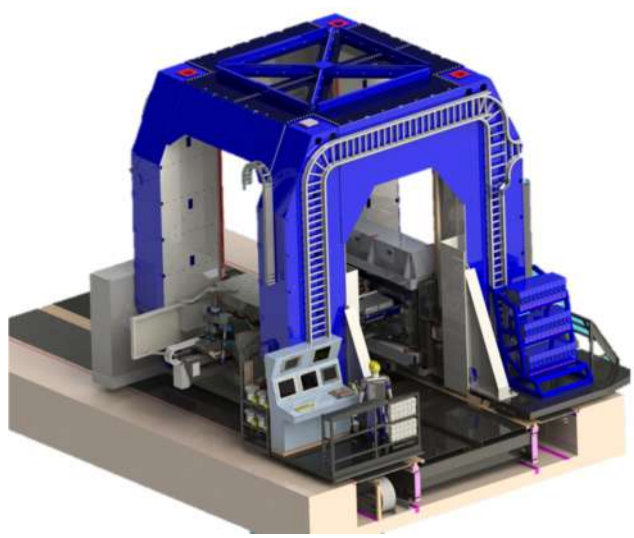

Figure 8 PAL machine structure was not duplicated in the test bench.

Critical components of fastener feed systems are notoriously among the most challenging to make reliable in an automated fastening machine. The intricacy of mechanisms and high speed at which fasteners are fed subject the parts to wear and tear. Injectors, which must stop an air-blast fastener and then place it into the feed-nose of the machine, without damaging the fastener, are chief among the critical components and one of the most difficult to make reliable. To combat this challenge, test benches were dedicated to cycling thousands of fasteners in order to ensure the most robust system possible. For PAL, two styles of injectors were tested and the best one selected for implementation.

Risk Mitigation: Integrated Testing

Another way to mitigate risk was to plan a test that integrated the fastening machine, tooling and full-sized lower wing panel for the first time, months before production would start at the customer site (Figure 9) as early as possible.

Shortly after the first of the machines and tooling were built and independently tested, they were brought together at the supplier's factory for the first "Integrated System Test". A test panel was supplied by the customer.

Many technical aspects (i.e. the mobile machine feature, integration with the tooling, setting wing panel configuration, and proving clamping methodologies) were addressed and highlighted. This hastened development of the system as a whole and mitigated many smaller risks to the projects future. No major issues were found.

Integrating control systems for all these assemblies was reviewed and revised, saving development time at installation. Test part programs were used to also clarify how the system would be run in production.

Figure 9 PAL Integrated Test at supplier facilities.

Risk Mitigation: CAD Simulation

Many delays for large scale projects can be attributed to unnecessary work done to correct mismatches between equipment and the facilities infrastructure that supports them. The need to reroute conduit, cable ways and pneumatic lines; re-pour concrete; or replace structural members is not uncommon. Checking 3D models across the various subsystems in one package was essential to avoid issues in utilities and foundation layouts before they happened and minimize the amount of rework. For PAL however, simple 3D model verification would not catch enough potential issues because of the number of interacting subsystems that occurs throughout the system. In addition to simply checking 3D models, 3D simulation was effectively used to realize the impacts of these interactions. This tool in addition to pre-released prints allowed all parties to not only check for inconsistencies but highlight areas that needed more focus for the entire team before any hardware existed.

Risk Mitigation: Single-Piece Machine Shipping

The ability of this system to move machines to any of the four production lines or into either of the two maintenance bay lines provided a unique benefit to the program. The challenge of the 30 month time constraint necessitated an investigation into shipping the machines as complete assemblies to save on time required to tear down and reassemble the structures onsite. This would also reduce risk of rewiring and reduce the touch-time of the equipment.

The completed machines measured 28' x 28' x 23' and weighed over 60 tons. The over land journey is about 35 miles thru the Seattle metropolitan area. Sixty tons is a relatively easy load to distribute to meet highway safety rating loads but the height and width of the load eliminated most routes due to overpass and infrastructure obstructions. Fortunately, the proximity of the customer site to the supplier provided an opportunity to capitalize on local marine industry for shipping the machines.

The majority of the trip could be covered by maritime routes through the waters of the Puget Sound and Lake Washington which are connected via a lock system. The balance of the trip would require an over-road route from the supplier's site to the customer's private rail yard in Everett, a train trip down one of the steepest grades in the United States (5.6% grade) to the Port of Everett Mount Baker Terminal, crane loading and unloading of a cargo barge, and a short private-road route into the customer's facility. Although the means had been established, the ability for single-piece machine shipping to succeed was still dependent on solving numerous engineering and logistics challenges. However the customer and supplier agreed that the benefits (risk mitigation and schedule gain) would make the efforts worthwhile.

So work began getting the machine capable of the two short overland routes, one to the rail yard and one to the building. There were to be nine machines in total for the initial contract so it was important to minimize the amount of disposable hardware required for the trip (Figure 10).

Figure 10 Transport dollies are mounted prior to departure. The orange frame is added and covered in shrink wrap to protect the machine for the duration of the trip.

A load of 60 tons is well below the limit for a railroad flatcar. On the other hand the dimensions of a width of 28' and a height of 23' posed a number of clearance problems. The height of the center of gravity was at the limit for a rail load of this size and the machine center of gravity was not symmetric perpendicular to the length of the flatcar, which is a requirement for rail transport. Because the load was so wide setting it on the rail car off center opened the possibility of interferences with obstacles such as signals, signs and foliage along the sides of the track. Since the load limit of the flatcar was in no danger of being violated it was determined concrete blocks could be strategically placed to center the mass of the system and bring down the height of the center of gravity while maintaining the minimum overhang on either side of the flatcar.

In an effort to mitigate risks associated with railcar transport, extensive FEA was performed as well as flatcar structure weld stress analysis and test runs down the 5.6% grade whereby acceleration data was collected and clearances were verified. The need to satisfy stringent safety requirements also drove the requirement for additional chains to prevent any possibility of the load sliding during the rail leg of the trip.

Figure 11 the barge crane with machine suspended moving away from the loading area to transfer the machine to the transport barge.

Acquiring a crane with the capacity to move a load of this size off the rail car and onto a cargo barge turned out to be easily achieved by employing a barge crane. The barge crane could lift the load directly from the rail car and, under the power of a tug, move out into open water and transfer the load to another waiting barge. See Figure 11. Once on the cargo barge, it was possible to move the load all the way to the southern shores of Lake Washington via the Ballard locks.

The concrete apron where the machine would be offloaded at the customer site was built early in the 20th century. Its age and the use of older building techniques made it necessary to prevent substantial outrigger loading within 30 feet of the water's edge, and a 30 foot setback would make using the barge crane impossible. In addition the depth of the water drove the need for a very low draft barge. Because the area was so shallow, an underwater survey was performed to determine if there were any obstacles preventing the close approach of the cargo barge and to select the precise landing location. With the survey information, it was calculated that a crane to reach of 70 feet from slewing center was needed to lift the machine from the front of the delivery barge. To help ease concerns over the imparted load of the outriggers and to improve scheduling dilemmas it was agreed to use two cranes for the off load at the customer site. See Figure 12

Figure 12 crane layout for the machine lift at the Boeing Renton site.

The machine was brought to rest between the two cranes where the transport dolly assemblies could be installed for the final move to the production facilities. From here the final move is just a couple of hundred meters to the maintenance bay where a customized bridge crane (the "transporter") would be used to move the machine into the factory. The same transporter is used to facilitate mobile machines and offline MRO for the life of the program.

Lessons Learned

Despite best efforts, not all technical risks could be completely mitigated. The fundamental reasons for this were differences between test bench and actual production machine (previously discussed) as well as limited test panel testing during preliminary acceptance.

The lower panel integrated test panel did not reveal tool clearances common to upper panel and consequently, the requirement for additional upper panel stringer-side anvils was not discovered until too late. This resulted in hand work until new tools could be fabricated. Had NC tryout been performed in CAD prior to actual production runs, this problem could have been avoided too.

The technology challenges that remained undetected during pre-qualification efforts and their causes are identified in Table 2. Due to lack of early detection, each of these technology challenges benefited from "Maximized Development Time". Recovery plans were created to minimize schedule impacts.

Table 2. PAL Technology Challenges and Cause.

TECHNOLOGY CHALLENGES	CAUSE
Silicone contamination affecting rivet interference.	Silicon O-Ring Lubricant in Rivet Cartridge Feed System.
Rivet interference inconsistency affected by ball screw drive oscillation.	Difference between test bench and actual machine structural stiffness.
Rivet smear inconsistency	Differences in assembly tolerances of machine positioning axes that were omitted in test bench.
Additional straight and offset stringer-side anvils required to clear upper panel Side-of-body structure.	No NC tryout in CAD to verify clearances.

Final Solution

Technology: Ballscrew Squeeze Fastening

The latest fastening process uses a ballscrews to produce the squeeze forces needed for forming rivets or bolt collars. The new process is achieved using a combination of force and position control and is capable of forming up to 40,000 pounds of force at rates of up to 200,000 pounds per second while holding the part location to within +/- 10 thousandths of an inch.

This process is described in detail in two SAE Papers titled:

- "Integrated Ball-Screw Based Upset Process for Index Head Rivets" (15ATC-0281#)
- "An Automated Production Fastening System for LGP and Hi-Lok Titanium Bolts for Aerospace Wing Manufacture" (15ATC-0149#)

Figure 13 Rivet forming process head, V-side.

Technology: Precision Positioning

In previous panel assembly lines, fastening operations were separate from part indexing, tacking and precision hole drilling for follow-on assembly stages. The PAL system relies on precision tooling and machine positioning elements to bring all of these manufacturing steps together. This also increases the capability of the system to include leading edge trimming, precision hole drilling in the Side-of-Body area and part probing.

Machine mobility was a requirement to reduce the impacts of maintenance activities to production. However, the machine design still incorporated precision rails for accuracy to enable accurate machine positioning to support root end hole drilling. An intermediate sled was designed to maintain precision and allow for the mobility feature.

The machine and tooling designs were further integrated by mounting both subsystems on the same bases (Figure 14). This reduces the effects of foundation settlement because the system settles as a monolithic assembly. Tooling routines and machine alignment verification procedures were also unified by using the same alignment system and targets.

Figure 14 Machine and Tools use the same base structure to maintain alignment and reduce differential movement.

Technology: Innovative Tooling

By collocating the tooling, material handling and automation design teams, integration efforts continued throughout the program, emergent issues were more efficiently addressed and integration was optimized. The following examples of design features came as a result of this collaborative effort:

Figure 15 Machine and Tools were designed around each other, which optimized machine access without compromising integrity.

Reducing the tooling profile

Because fixed tooling was used to set wing panel configuration, automation equipment was required to work around tooling when fastening. Design goals for both the Tooling and the Machine were to minimize the shadow cast on the panel by the tooling, maximize the working area of machine, and reduce machine fastener-to-fastener move time. Some of these goals were not mutually exclusive. Typically, when trying to minimize the tooling profile, access requirements are identified upfront. In this case, the tooling was minimized but on multiple levels and weighed against machine cycle time. As the fastening head design matured, more changes were made to permit optimization of tooling dimensions in various directions, as well as the fastening head (Figure 15). This greatly increased access for the automated equipment and decreased processing time without compromising the integrity of the tool or machine.

"Shadow Complimented" Tooling

The tooling creates a "shadow" for the machine to work around when holding the part. By designing the next station in the assembly line with the tooling located in complimenting positions, the need to move the tooling for machine access during production is eliminated. Operator intervention is also eliminated increasing rate, reducing downtime and decreasing errors.

Figure 16 Tooling posts were placed in complementary positions from one cell to the next to avoid manipulating the tool during production.

Innovative Indexing

Reconfigurable tooling was investigated to accommodate aircraft variants. Initially this was considered a benefit but it came with the high cost of increased cycle time. The size of the tool blocked machine access to a high percentage of the panel area, increased machine moves and required a great deal of operator interaction. All of these issues would have added to the takt time and made balancing the system difficult. Instead, the panels design, stringer indexes and clamps were designed to accommodate variations in stringer thicknesses without requiring reconfiguration. These clamps could then be used for all the stringer locations and across different tools. Universal assemblies reduced costs, spares and confusion.

Concurrent Tooling Design and Commonality

With the schedule flexibility of subassembly design, component designs could wait until after other systems were more developed. For example, a major portion of the tooling structure was designed early in the project but the final index assemblies were delayed as long as possible. Changes to the aircraft design or the fastening machine could be identified in detail before finalizing the design of the indexes. This method was used on all subsystem designs which allowed for changes with other subsystems until very late in the project. By moving the final design dates for these subassemblies later in the project, the available design time was increased while still maintaining the original production ready dates.

Figure 17 Innovative Indexing accommodates aircraft variants without reconfiguration.

Another advantage of delaying subassembly design was related to commonality. As the various tools required for the PAL line were designed, there were many opportunities to implement commonality. This could be applied across the entire line and all the tools where possible. The stringer clamps are a great example of demonstrating the commonality advantage.

Lessons Learned

Overlapping and extending the design time for subassemblies created the problem of increasing inspection periods. Conventionally, inspection is only executed with the completion of the entire assembly. In this case, inspection was required over a much longer period, scattering resources. The overall benefit of reduced project time and increased design time outweighed this consequence. Going forward, planning should account for the increase and just-in-time inspection requirements.

Technology: Mobile Machine and Offline MRO

When automation equipment is maintained or repaired, the system must absorb the associated downtime. In order to increase productivity of PAL, the fastening machines were equipped with a "mobile machine" feature allowing a machine to be removed and replaced from the production area within 20 minutes while still maintaining precision alignment. This concept was developed to move routine maintenance offline as well as to minimize impacts to production as the result of a machine breakdown.

The PAL system is designed to allow any machine to be moved to any one of the four production lines for a total of eight production positions and the two maintenance positions (Figure 18). A significant benefit of the mobile machines is the dedicated area for machine maintenance and repair out of the production area. The maintenance bay has two fully equipped lines to operate, repair, troubleshoot and perform regular maintenance (PPM). This minimizes the impact to production while keeping the machines performing at their best and reduces MTTR. An additional benefit of the maintenance bay is the ability to offer a fully functioning machine that can be used to train operators and maintenance personnel.

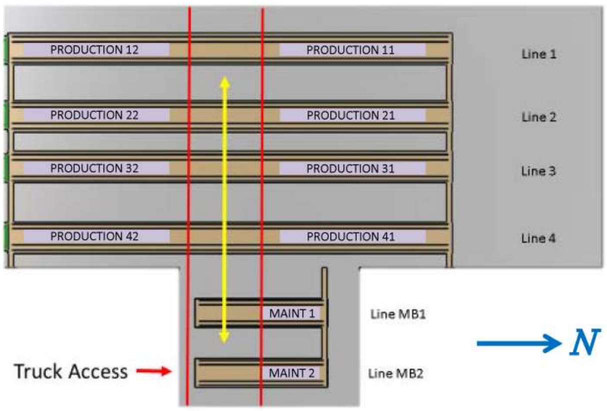

Figure 18 Machine cell layout. The yellow arrow indicates the machine transporter path.

The mobile machines are mounted to linear bearing guided "sleds" (Figure 19). Large guide pins help direct the large machine to the final position during loading. Precision clamping devices then secure the machine in a repeatable position and withstand machine operating loads. A servomotor-driven rack and pinion system and linear encoder readheads are incorporated into each sled. The sleds also contain power, air and networking quick connections which power the machine and enable the machine's CNC to command the sled.

Figure 19 Machine Sled

The machine transporter (Figure 20) is used to move machines from sled to sled and line to line. The transporter is a customized gantry crane designed with an 80 ton capacity. Three servo-hydraulic cylinders precisely lift and lower machines onto sleds. Cargo-handling twist locks connect the transporter to the machine and a slewing bearing allows rotation to orient machines properly with left-hand and right-hand production lines.

Figure 20 Machine Transporter

The machines, sleds and transporter teams were able to also integrate the different control systems. By monitoring the interactions of each subsystem, machine transfers were safer by automating where possible. This reduced the skill set required, provided mistake-proofing, and allowed the resident maintenance crew to operate the entire system without the need for specialized crane crews.

Technology: Semi-Automated Material Handling

Moving large parts through five positions of four PAL assembly lines is necessary to accommodate the manual and automated work that must be performed in order to build wing panels. Moving any parts in an assembly line is non-value added work, and thus must be performed as quickly as possible. History has shown that reliance on shared building cranes to move parts results in extended delays. Therefore, a dedicated monorail was installed to eliminate waiting for tied-up building cranes or crane operators.

But just having a dedicated manually-operated monorail would not be efficient enough. The limited time (approximately 20 minutes) allocated for wing panel moves from position-to-position in PAL demanded some type of automation. Rapid fully-automatic movement of parts is common in high-speed assembly lines, however, for parts as large as commercial airplane wing panels, this is usually cost prohibitive to automate entirely. Therefore, the time required for non-value-added part movement through PAL was minimized through use of a semi-automated monorail system that utilizes pre-programmed "upstream/downstream" paths but relies on manual intervention for controlling fine-tune movements necessary when loading and unloading wing panels from jigs. This system incorporates multi-directional and multi-task custom programming to move wing panels upstream and downstream between positions. Figure 21 shows the wireless handheld transmitter with "auto upstream" and "auto downstream" buttons used to control the PAL semi-automated monorail system. The seamless steps for moving a wing panel between PAL position 3 (P3) and position 4 (P4) are listed below to illustrate how "semi-automation" saves time.

1. Pressing "upstream" moves P4 bridge and carrier laterally to trunk line, engages bridge interlock, then moves carrier longitudinally through bridge interlock to P3 spur-line track switch.
2. Continue pressing "upstream" actuates the spur-line track switch and moves empty carrier through track switch and laterally along spur to within 18" of wing panel clamped in jig.

3. Continue pressing "upstream" lowers hoist to pre-determined elevation suitable for connecting spreader bar straps to wing panel.
4. Manual interlock-controlled operations are required for fine-tune movement of carrier closer to the jig to allow mechanics to connect straps to the wing panel. Hoists are then manually raised until a programmed load cell preloads are reached. Preloads are induced by the weight of the wing panel hanging from the straps. Once preloads are reached, hoists and carrier will no longer move away from jig until jig clamps are opened.
5. Manually open jig clamps and continue raising hoists and moving carrier under manual control to clear wing panel a safe distance away from the jig. Hoist and carrier creep modes are enforced when performing this manual operation.
6. After wing panel is 18" away from jig, semi-automated control may resume. Pressing "downstream" button raises hoists to wing panel fly height and moves carrier and wing panel through spur-line track switch to trunk line.
7. Continue pressing "downstream" button to actuate track switch and move carrier and wing panel down the trunk line and onto the P4 bridge.
8. Continue pressing "downstream" disengages bridge interlock and moves the bridge, carrier and wing panel laterally to P4 fixture.
9. Continue pressing "downstream" moves carrier in-line with the fixture hoists lower wing panel to predetermined elevation.
10. Manual control resumes for fine-tune loading of wing panel into fixture.

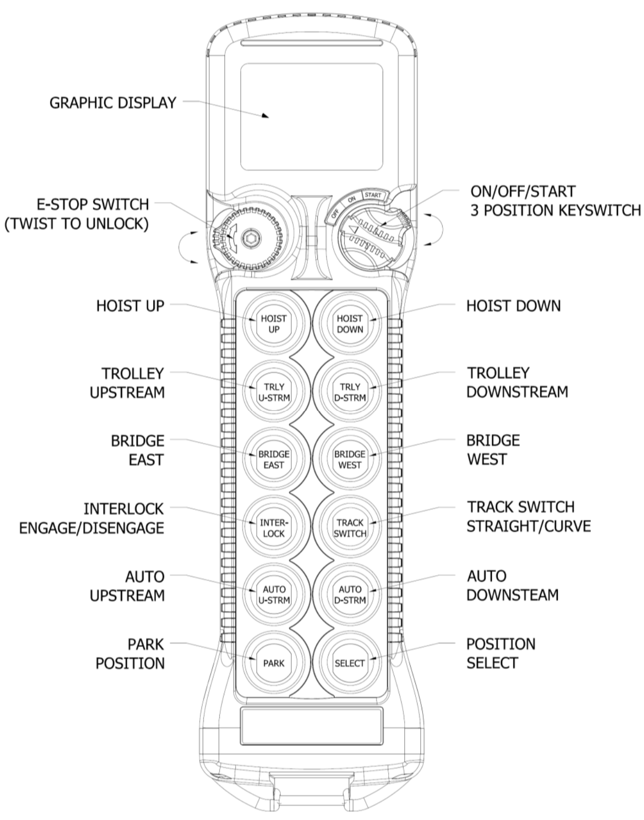

Figure 21. PAL Semi-Automated monorail has "Auto Upstream" and "Auto Downstream" buttons that allow wing panels to be moved quickly and precisely between two positions of the line.

Consistent programmed part presentation fosters trouble-free and most-efficient loading and unloading of parts. Bridges, bridge interlocks, track switches, carriers, hoists, and speeds are all controlled seamlessly with "auto upstream" and "auto downstream" buttons.

Hoist load cells with digital displays viewable from the ground provide part protection and guidance to operators when unloading wing panels from jigs. Force-feedback detects pre-load on straps and interlocks prevent operators from opening clamps (which would release wing panel from jig) before panel handling straps are properly pre-loaded.

At any time, the semi-automated direction of motion can be transitioned from "upstream" and "downstream" and the monorail will move accordingly. Bar code readers and bar code tape mounted along the length of all monorails enables any carrier to know its precise position within millimeters at any time.

Park button allows an empty carrier to be stored in pre-determined locations high enough so dangling straps are out of the way of personal walking underneath. Or, if a wing panel is hanging from the carrier (evidenced by load cell feedback), then the park button allows wing panel to be safely suspended from chains in pre-determined locations creating buffers between assembly line positions. Safe suspension hardware complies with ASMEB30.16 requirement to not leave a load suspended from hoist(s) unattended unless provisions have been made to provide auxiliary supporting means.

Lessons Learned

Fully-automated part transfer was not possible for PAL due to reliance on hoist wire ropes (between monorail carriers and spreader bars) and nylon straps (between spreader bars and wing panels) inherent to traditional wing panel handling. Wire ropes and nylon straps are subject to mechanical stretch which makes programmed fine-tune positioning impossible. It is not known whether an alternative method of handling panels which overcomes mechanical stretch might be feasible or cost effective.

Fully Integrated Safety Interlocks & Systems

Addressing safety not only in each of the project areas, but addressing safety on a complete system level was a requirement.

Diverse types of equipment integral to PAL necessitated satisfaction of a variety of safety standards. PAL monorail and crane systems satisfied ANSI B30 crane standards and personnel lifts satisfied ANSI A92 lift standards. Compliance to these standards was straight forward due to the direct applicability of the standards. PAL fastening machine risk assessment was based on ANSI B11.23 (Safety Requirements for Machining Centers and Automatic, Numerically Controlled Milling, Drilling and Boring Machines) which is written around traditional, mass-produced, fully-enclosed machining centers. In some cases, extensive tailoring of ANSI B11.23 requirements was necessary to conform to a large machine system like PAL while meeting the intent of the original safety requirements.

The overall Panel Assembly Line risk assessment which takes into consideration the interactions of the various types of equipment was based on ANSI B11.20 (Safety Requirements for Integrated Manufacturing Systems). Compliance with this standard drove the need for fully integrated safety interlocks with supervisory control. The integrated design team approach for PAL afforded a level of interlocking and safety systems integration that might otherwise not have occurred. Table 3 summarizes some of the risks and how they were mitigated with interlocks and safety systems.

Table 3. PAL Safety Risks and Mitigation.

SAFETY RISK	MITIGATION
Trip hazards associated with elevated machine beds and rail systems.	Extensive network of flush hinged floors.
Fastening machine colliding with personnel, mobile lift, foreign object or another fastening machine.	Bumper switches, safety sweep scanners and yellow painted hazard areas on floors.
Monorail moving wing panel into fastening machine or fixed personnel lift that is raised.	Interlock preventing monorail motion unless fastening machine is clear or personnel lift is in stowed position.
Machine crashing into monorail or wing panel.	Interlock preventing machine motion unless monorail is clear.
Monorail presenting wing panel to jig with clamps closed.	Interlock preventing monorail from approaching empty jig unless clamps are open.
Opening jig clamps prematurely and allowing wing panel to fall on floor.	Load cell pre-load interlock.
Monorail unloading wing panel from jig with jig clamps closed.	Interlock preventing monorail movement after strap pre-load is reached unless clamps are open.
Monorail hoist attempting to lift part when part is hung up.	Load cell over-load interlock.
Crashing wing panels suspended from separate monorail carriers into each other.	Traffic control interlocks with load cell feedback to detect wing panel presence.
Fastening machine colliding with jig clamp in wrong opened or closed state during fastening or routing.	Jig clamp state interlocks.
Raising floor-mounted personnel lift into monorail-suspended wing panel.	Interlock preventing lift motion unless monorail and wing panel are clear.
Misalignment of bridge crane (transporter) with fastening machine or sleds	Machine sled interlock pin and bridge crane bar code reader to ensure proper alignment.

A traffic-control PLC monitors the states and locations of machines, carriers, wing panels (based on load cell feedback), sleds, tooling and the transporter to ensure safety. Many PAL interlocks are enunciated by color-code stack lights that provide feedback and guidance to workers. The meaning of the light colors is posted on tools and equipment as shown in Figure 22.

Figure 22. Placards mounted to PAL jig provide explanation of colored stack lights that work in conjunction with control interlocks.

The elaborate safety systems and interlocks supporting PAL serve double duty in that they ensure worker safety, but they also avoid costly accidents that would jeopardize production throughput.

Lessons Learned

At the time PAL was implemented, ANSI B11.25 (Safety Requirements for Large Machines) had not yet been released. Although ANSI B11.25 scope includes machines with work envelopes as small as two cubic meters (much smaller than PAL) it is likely that the requirements of this new standard will more directly apply to PAL and require less extensive tailoring.

Summary/Conclusions

With production ramp up underway, the PAL program has proven to be a great success. The program schedule was based on meeting the production start date for a new aircraft. At the time of this writing, the first panels for the new aircraft are in process (Figure 23). Processing of the panels has been streamlined in half the space compared to the legacy method. Material handling is now close to autonomous control with no need for specialized personnel. Part flow is straight forward and has eliminated tens of non-value added lifting activities. Panels are accessible for inspection while in-process. The assembly line is very clean and clear adding to safety improvements. And most importantly, the customer has reported that the quality of panels produced by the new PAL (measured by panel contour and fit as well as fastener quality) exceeds the quality of panels produced via the legacy methods.

Figure 23. PAL producing first ship set of new aircraft panels.

Regarding implementation, the communication tools used were extremely effective at identifying and communicating the important dates. Changes were accommodated between teams because each team had advance notice of the overall progress. There were multiple contractors onsite for most of one year of the program and issues were minimized and prioritized very effectively. Some tooling designs were delayed long enough to avoid expenditures for multiple iterations because close to the final versions were used for initial production. The tooling profiles were designed well within required envelopes ensuring machine access as planned. Machine performance was maintained even with the added mobility features and verified throughout the entire assembly line. Changes were made throughout the project (afforded by Maximized Development Time) and the amount of value added changes far outweighed the non-value (repair or correction) changes.

By identifying integration opportunities throughout the project, this method of project management also yielded a more cohesive assembly line and avoided addressing these opportunities after production starts. The methods of project management and tools used during this project will shape how follow-on projects are managed by the customer for the foreseeable future.

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- American Industrial Co.
- Dutton Electric Co.

Definitions/Abbreviations

CAD	Computer Aided Design.
CNC	Computer Numerical Control.
FEA	Finite Element Analysis.
HMI	Human Machine Interface.
MTTR	Mean Time To Repair.
MRO	Maintenance, Repair and Operations
NC	Numerically Controlled program.
PAL	Panel Assembly Line.
PPM	Planned Preventative Maintenance.
Takt time	Factory production time interval.
Tooling	Fixtures or tools that set wing panel configuration.