2020-01-0010 Published 10 Mar 2020

Case Study on the Challenges and Responses of a Large Turnkey Assembly Line for the C919 Wing

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Citation: Forbes, M., "Case Study on the Challenges and Responses of a Large Turnkey Assembly Line for the C919 Wing," SAE Technical Paper 2020-01-0010, 2020, doi:10.4271/2020-01-0010.

Abstract

Design and production of an assembly system for a major aircraft component is a complex undertaking, which demands a large-scale system view. Electroimpact has completed a turnkey assembly line for producing the wing, flap, and aileron structures for the COMAC C919 aircraft in Xi'an, China. The project scope includes assembly process design, material handling design, equipment design, manufacture, installation, and first article production support. Inputs to the assembly line are individual component parts and small subassemblies. The assembly line output is a structurally completed set of wing box, flaps, and ailerons, for delivery to the Final Assembly Line in Shanghai. There is a trend toward defining an assembly line procurement contract by production capacity, versus a list of components, which implies that an equipment supplier must become an owner of production processes. The most significant challenge faced was the amount of front end engineering work required to develop detailed assembly processes and reconcile them with the customer, who remains the actual process owner. Other challenges include aircraft maturity delays, design changes due to process definition evolution, factory environmental conditions such as dust and varying temperature gradients, and cultural and communication challenges both internal and external. The result achieved by Electroimpact is an assembly line system composed of an integration of assembly tooling, special process equipment, NC machine equipment, inspection equipment, material handling and logistics equipment:

- Two robotic drilling cells integrated with both stationary and mobile tooling.
- Integrated wing major assembly cell with manual assembly jigs and large CNC wing drilling machines.
- Twenty-three other manual work stations.

New technology developments implemented include:

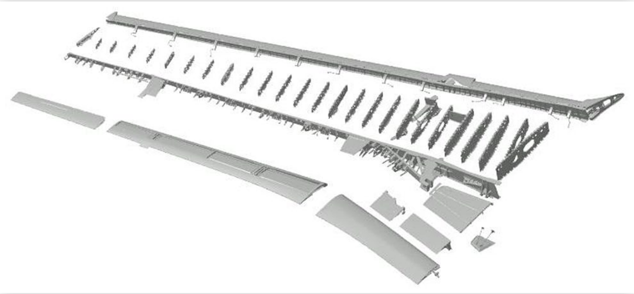
- A new high-curvature nosepiece on the robot end effecter to enable accurate drilling and countersinking on the LE Spar D-Nose section.
- A new application and delivery system for single-sided temporary fasteners for wing panel drilling.
- Tooling design to accommodate large temperature variations.

Introduction

The COMAC C919 is a new design single aisle commercial airliner, developed to compete in the 150-170 passenger space. Electroimpact was contracted to design and build an assembly line for both the Wing box and the Flaps and Ailerons. Individual component parts and a few small subassemblies enter the factory, and structurally complete wings and flaps are shipped out of the factory to Shanghai for integration to the fuselage at the Final Assembly Line (FAL).

The project is broadly divided into eight major subprojects: Leading Edge Spar assembly (LE), Trailing Edge Spar assembly (TE), Wing Major assembly (MAJ), Wing Laydown, Flap & Aileron assembly (FA), LE & FA Drilling Robots, Wing Box drilling machines (LTD), and NC Programming for the machines. The aircraft structure assembly scope is shown for reference (Figure 1). The project was executed by engineering

FIGURE 1 Project Scope: Assembly of all components shown (Skin panels hidden for clarity).



teams in Electroimpact's US, UK, and China offices. Challenges arose in organization, geography, culture, and above all, communication.

Two important features stand out in the execution of this project. First, the scope of the project included not only equipment design, but overall system design and detailed assembly process design. Second, the customer requested a proven rate of production as acceptance criteria. These small points have substantial consequences.

A significant benefit of such a large scope is the opportunity to coordinate technical aspects of multiple different designs and to deliver a unified operational concept to improve the operational character of the assembly line system. A corresponding challenge faced in such a large scope was in the definition, documentation, and communication of the whole system design, at a detail level.

Other challenges included late delivery of frozen engineering data and environmental conditions such as temperature instability.

This paper seeks to describe some of the strategic challenges faced and propose better alternatives when the solutions employed did not work well, with a goal to clarify the setting of expectations for both customer and supplier in a similar context.

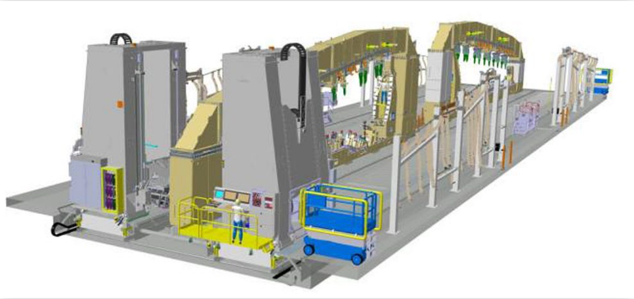
Production System Characteristics

The final production system as implemented is a coordinated arrangement of 25 discrete work stations (Appendix 1 - Stations List). The LE Spar is a one-piece aluminum beam, and the structure is built up in three stations. The TE Spar is built up from three aluminum beams, two transition boxes between flaps and ailerons, and an aux spar beam; built up in five stations. The LE Spar, TE Spar, Ribs, and Skin Panels are all assembled together in the wing Major Assembly Jig. The finished wing structure is extracted from the MAJ and laid down on a trolley, to run through a 5 position Laydown flow line. In Laydown, systems such as hydraulics and fuel piping are installed, the fuel tank is tested for leaks, and the wing box is measured at critical interface points via laser tracker. Smaller subassemblies are also built up separately for later incorporation, including the LE Wing to Body Fairing and several cover panels on the TE Spar.

The Flap and Aileron line assembles the Inboard Flaps, Outboard Flaps, and Ailerons in an adjacent section of the factory (Appendix 2 - Factory Layout). Development of tooling and automation solutions was shared across both lines, which brings beneficial commonality to the system in both automation and tooling design.

Fitting all of the necessary work stations into the given factory building area is a common challenge. The ideal flow of parts should be in one direction, in our case from right to left on the layout map (Appendix 2). This was in conflict with the ideal arrangement of the MAJ cells, which occupy the largest footprint. The MAJ and LTD machines are arranged in a straight line, with one LTD machine serving the top skin side of both left and right hand jigs, and a second LTD machine serving the bottom skin side (Figure 2). The downside of the tradeoff is that the TE parts flow from the center of the factory backwards to the MAJ, but in this case it is a negligible impact to the factory flow. The benefit gained is that there is no need to move the LTD machine from line to line, and the MAJ cell maintains clear and open access for all work operations.

FIGURE 2 MAJ Cell Layout.



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Automation Design

Automated hole drilling is applied as much as is practical, with tooling designed to optimize access for the automation. The first application is Electroimpact's Accurate Robot Drilling Machine on the D-Nose skin to LE Ribs structure. A technical advancement is the application of a new design nosepiece [1] to enable accurate drilling and countersinking on the high-curvature section of the D-Nose (Figure 3). This robot is applied on both the LE D-Nose and the Overwing Panel in the same cell.

The Flaps cell is laid out to use mobile jigs: INBD Flap, OTBD Flap, and Aileron jigs. The robot drilling machine applied on the Flap and Aileron panels is nominally identical to the LE robot; the only difference is application of a standard nosepiece versus the high-curvature nosepiece on the LE. Using an otherwise common design solution proved to be a significant benefit.

FIGURE 3 New nosepiece design for high curvature LE application (left) compared with standard nosepiece applied on FA (right).

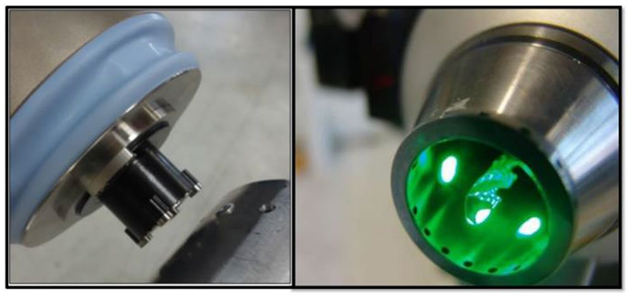

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FIGURE 4 LISI CLY™-61 Fasteners and Cartridge Loading System.

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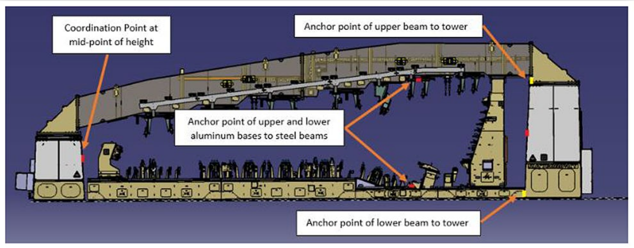
FIGURE 5 Wing MAJ Layout Diagram.



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In the MAJ station, the LTD machine is applied to drilling holes between the skin panels and the rib & spar structure. New technology developed for this application is the automated installation and handling of LISI CLY™-61 fasteners (Figure 4), to increase system reliability compared to previous systems [2] which employed blow tube fastener delivery.

In practical terms, the specification of the automated equipment and its application was left almost entirely to the supplier. There are two notable risks: the customer may not get what they want or need, and the supplier could ambitiously introduce a great deal of new and unproven technology. The strategy employed was to propose a limited quantity of incremental enhancements, as described above; this proved to be a successful strategy.

Tooling Design

Large temperature swings were a known requirement in the concept phase, so the tooling design was planned to accommodate accordingly where applicable. The LE and TE Spars are long and slender, so thermal expansion becomes a one-dimensional problem. Tooling was designed with steel structure for rigidity, with aluminum interface plates for mounting tooling details. The interface plates are mounted on linear bearing rails to permit controlled thermal expansion in the long (X) axis.

Common tooling interfaces (flags) were employed between stations to speed part load and unload operations [3]. Between stations, thermal growth was accommodated in the flag mounting scheme also. As in the case of automation described previously, this is an incremental enhancement of technology that is performing well, and is largely enabled by the strategy of contracting several tooling packages to one single supplier.

Thermal design for the wing MAJ is more complex. The wing is held vertically to permit clear access to the LTD machine for drilling on both top and bottom sides (Figure 5). In considering temperature change, the problem becomes two-dimensional. Similar aluminum interface plates are used in (X), plus aluminum tower sections to accommodate thermal growth in the vertical direction (Y). The jig design is End-Constrained, meaning that the top beam of the jig is fixed at the root end and allowed to float in (X) at the tip end [4].

While temperature change was well accounted for, and temperature gradient from floor to ceiling was understood to exist, transient change in temperature gradient was an aspect that was not considered. Vertical temperature gradient was measured to be around 1C warmer at the top beam compared to the bottom, but not always. This gradient was observed to fluctuate over the course of hours, and even invert - where the upper beam temperature becomes lower than the lower beam. This proved problematic while performing metrology work. Thermal expansion in the long (X) direction is straightforward to account for in metrology software by scaling, but different expansion characteristics in different areas of the jig were extremely difficult to deal with. For example, when the temperature gradient inverted, the upper area of the jig contracted while the lower area expanded. This is designed to accurately match the thermal expansion characteristics of the wing, but makes the metrology work difficult. The solution found was to develop a detailed process, including documented restrictions in environmental conditions, to be considered any time that the jig needs metrology recertification.

This is an area that would benefit from further study to better quantify the effects of transient thermal conditions on fixed tooling measurements.

Detailed Production Process Design

Front-End Engineering and Process Ownership

An amount of front-end engineering design was performed by the customer prior to releasing the project for bidding. The result is a baseline set of processes and requirements for the assembly line. In the proposal development stage, Electroimpact similarly performed analysis to further develop requirements sufficient to develop a statement of work (SOW) and bill of materials (BOM). This analysis was developed on the basis of experience with similar work, and many detail points remained as assumptions. One key assumption was implicitly made - that the customer would fill in the details in a satisfactory manner and timeframe. These details include points such as Condition of Supply (COS), assembly datums, detailed assembly requirements for individual parts; and are items that an equipment supplier needs to inform their design.

Problems were encountered when these details were not developed by the customer. The response was to develop and document these details ourselves. This does create opportunities for innovation, but also the need for an additional approval process. Two common examples are (1) definitions of pilot holes and tooling holes to be provided as COS into the factory, and (2) definitions of assembly datums to determine how to align parts relative to each other. The datums were particularly problematic to define (see further comments about MBD). At this point it is important to note that the direct customer in this case has the role of airframe builder, while the aircraft designer is a separate organization. This adds additional complexity to the approval process. The impact to the project was delays in execution while these details were worked through.

We propose that in order to delegate detail process definition to a supplier at a large scale, an ideal contracting strategy is to first initiate a design contract to complete the Front-End Engineering, fully define the processes to be carried out, and detail the list of equipment (BOM) needed to accomplish every process. Then a lump-sum fixed contract can be employed to design and deliver every item on the BOM. Such a strategy should reduce, if not eliminate, the costly approval loop that has been described (see Appendix 3). The key point is that this strategy fosters innovative thinking while respecting the actual ownership responsibility at the detail level.

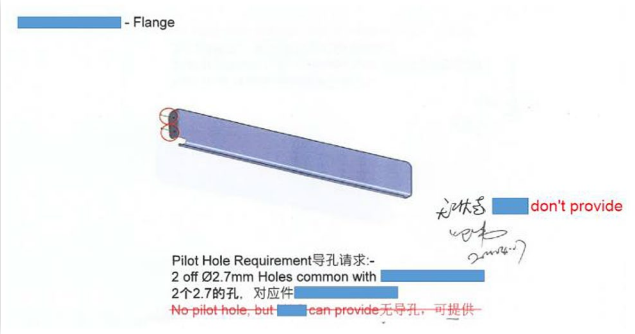
MBD and Technical Communication

Model Based Definition (MBD) was used extensively by the aircraft designer. In practice, the MBD was often incomplete and occasionally even incorrect relative to common standards (i.e. ASME Y14.5 GD&T callouts). Manufacturing and assembly processes had some requirements listed in the model attributes, but details such as pilot hole and tooling hole locations as COS were absent. Communicating pilot hole requests and confirming assembly datums proved to be a serious challenge.

Pragmatically, in this case the most successful approach found for resolving these issues was to reduce to the lowest common denominator: capture CAD screenshots to MS PowerPoint, print out slides on paper, and present to the customer for signature. Signed papers were then scanned and archived (example, Figure 6). This applied to elements such as assembly datum schemes and pilot hole locations. It remains problematic for the information communicated in these papers to work its way upstream in the customer's manufacturing and production organization.

There is a real need and great opportunity for better systematic tools for developing, presenting, approving, and archiving this kind of technical communication. Poor tools in this area only complicates the already problematic issue of process ownership.

FIGURE 6 Lowest Common Denominator Communication Method - Example pilot hole request, with subsequent alterations.



[redacted] - Flange

[redacted] don't provide

Pilot Hole Requirement导孔请求:-
2 off Ø2.7mm Holes common with [redacted]
2个2.7的孔，对应件[redacted]
~~No pilot hole, but~~ [redacted] ~~can provide无导孔，可提供~~

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Production Rate Capacity

Production rate capacity is a contentious topic. Contract language proposed by the customer expected the production system to demonstrate a given production rate capacity as a condition of acceptance. From the buyer's perspective this should reduce the risk of the contract by placing all risk upon the supplier. This expectation could be feasible if the supplier were the owner of every process and person employed in the production.

In reality however, the airframe builder (customer) supplies the people and, more importantly, carries ownership of the detailed production process. Therefore, the most that a supplier can commit to is to *design according to a production rate*. In all written communications, care was taken to hold to this principle: a supplier can develop and present analysis for review, but the analysis cannot be ultimately binding due to unknown conditions and requirements that are outside control of the supplier.

The conclusion proposed is that despite an attractive appearance, simply requiring that a supplier be responsible for things outside their realm of ownership does not reduce overall project risk.

Organizational Challenges and Design Management

As noted previously, the project work was broken into eight separate functional engineering groups, with multiple disciplines in each. LE Spar, TE Spar, and Laydown tooling was designed and implemented by engineering teams in Electroimpact's UK office. Wing MAJ and Flap/Aileron tooling was designed and implemented by Electroimpact's US office. Automation design and implementation was by three different US based groups - Robots, Machines (LTD), and Offline Programming (OLP). Electroimpact has a highly innovation-minded company culture, which presents organizational challenges to ensure that all of the engineering groups are coordinating together.

Simple organizational culture challenges are complicated by CAD design preferences. Each group has its own preferred CAD system, including the case of customer-mandated CAD system and version for deliverable tooling design. This created some issues in keeping the top-level factory model up to date.

The overall strategy that worked well was mandated use of a Product Lifecycle Management (PLM) system by all engineering groups, to the extent possible. Design data across offices in the US, UK, and China was synchronized automatically in the background. Overall machine designs were translated to Catia CGR format for factory level visualization. While the use of a PLM system proved essential, and periodically updating CGRs can work, the whole scheme is not completely without flaws. On occasion there were problems with configuration management in manufacturing; typically occurring when work was performed outside the PLM system.

In total five different CAD systems were employed in this project. The difficulty in this is that it fosters an attitude of isolation - without visibility of the neighboring context, each group tends to work in isolation from the others. It is a real situation that each group design group individually prefers their own tool set, but the project as a whole suffers from lack of commonality in the design data. This is an ongoing issue that Electroimpact is taking strategic steps to address internally.

Summary/Conclusions

The assignment of a large-scope project to a single supplier is a great opportunity for a well-controlled and cohesive system design. But assigning the project to one supplier does not alleviate all risk on its own; a timely approval process and supply of necessary inputs remain critical for a good project outcome.

Successful project execution also involves being deliberate about new technology introduction and aggressive about maintaining internal cohesiveness among multiple design teams. To this end, a common, detailed, and accessible view of the system design would be a great benefit, but today's tool set of presentation slides and spreadsheets remains lacking.

The real disconnect between the developer of process details (supplier) and owner of process details (customer) highlights the need for a shared system view that extends from the high level plan through to the low level details to enable robust process development, communication among all affected parties, and a timely approval process. We have seen progress by use of MBD for this communication, but there are rich opportunities for improvement.

Diligently working through these challenges, Electroimpact has brought this assembly line into production. Lessons learned should lead to improvements in project execution, for the benefit of all.

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Contact Information

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Definitions/Abbreviations

BOM - Bill Of Material; at a high level it is the list of contract deliverables

CGR - Catia Graphical Representation; lightweight visualization format

FA - Flap & Aileron

FAL - Final Assembly Line

LE - Leading Edge Spar

LTD - Lean Technology Drilling; name of the wing box drilling machine

PLM - Product Lifecyle Management system

TE - Trailing Edge Spar

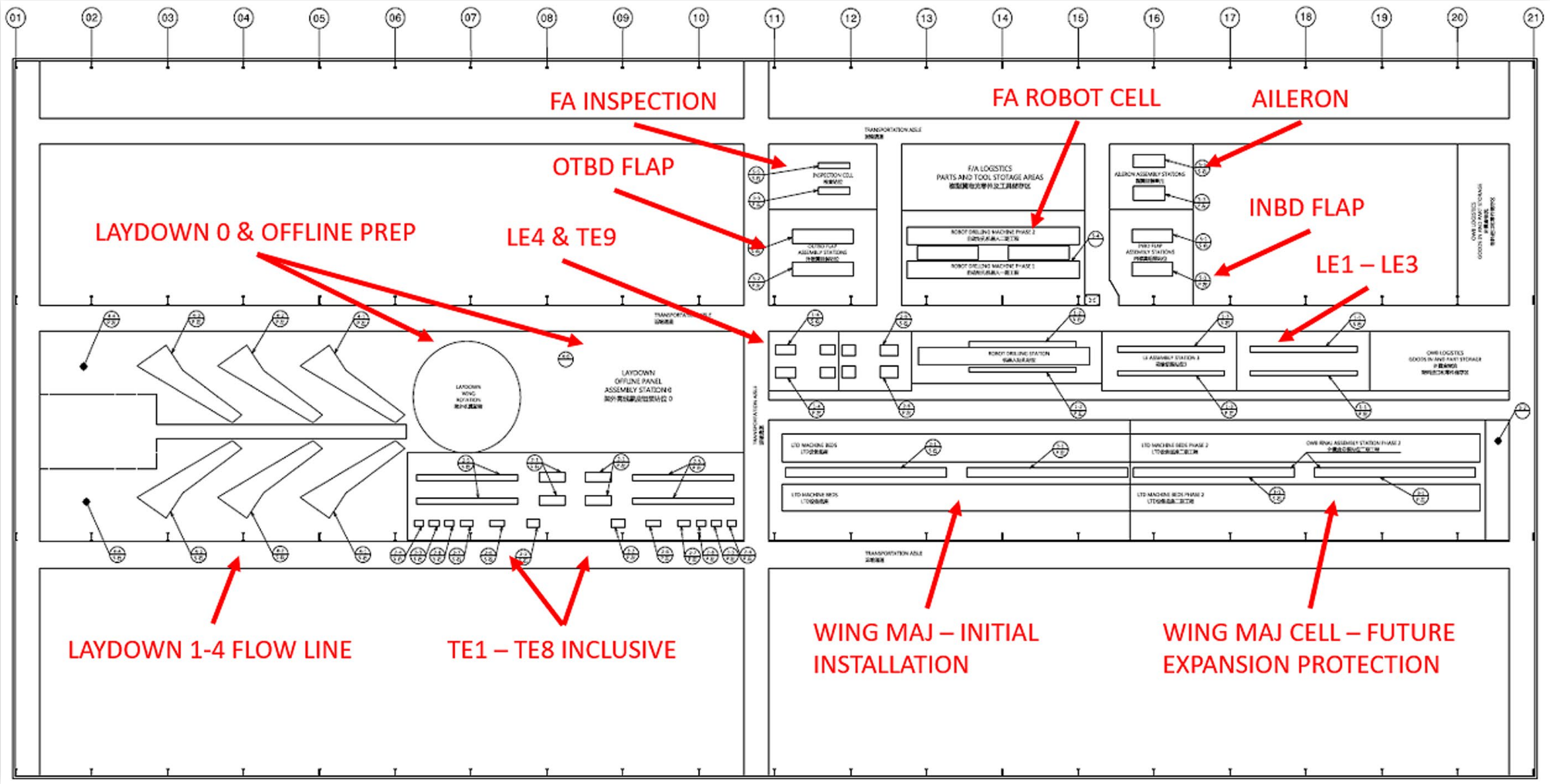
MAJ - Wing Major Assembly Jig

OLP - Offline Programming; software for creating, simulating, and posting NC programs

Appendix 1: Factory Stations List

Station Number 站位号	**Station Name** 站位名称	**Station Description** 站位描述
1-1	Leading Edge Station 1 前缘站位1	Structure Build 结构组装
1-2	Leading Edge Station 2 前缘站位2	Robot Drilling 机器人钻孔
1-3	Leading Edge Station 1B/3 前缘站位1B/3	Skins Installation; Clean & Deburr & Fastening 安装蒙皮；清洗&去毛刺&紧固
1-4	Leading Edge Station 4 前缘站位4	Root Fairing Build 安装翼根整流罩
2-1	Trailing Edge Station 1 后缘站位1	TE Inner Spar Sub-Assembly Jig 内后缘组件型架
2-2	Trailing Edge Station 2 后缘站位2	TE Aux Spar Sub-Assembly Jig 后缘辅助梁组件型架
2-3	Trailing Edge Station 3 后缘站位3	KINK Box Sub-Assembly Jig KINK盒组件型架
2-4	Trailing Edge Station 4 后缘站位4	TE Aileron Box Sub-Assembly Jig 副翼舱组件型架
2-5	Trailing Edge Station 5 后缘站位5	TE Spar Main Assembly Jig 后缘总装配型架
2-6	Trailing Edge Station 6 后缘站位6	TE INBOARD FLAP COMPARTMENT Sub-Assembly Jig 内襟翼舱组件型架
2-7	Trailing Edge Station 7 后缘站位7	TE INBOARD FLAP - OUTER FIXED PANEL Sub-Assembly Jig 内襟翼外壁板组件型架
2-8	Trailing Edge Station 8 后缘站位8	TE LOWER ROOT PANEL (UWP) Sub-Assembly Jig 翼根下壁板组件型架
2-9	Trailing Edge Station 9 后缘站位9	TE WING ROOT PANEL (OWP) Sub-Assembly Jig 翼根上壁板装配型架 STAGE 01 & STAGE 02 JIGS 站位01&站位02夹具
3-1	Main Assembly Fixture 总装型架	Wing Structure Build, Pylon operations 翼盒总装，吊挂加工
3-2	Rib Prep Cell 肋板准备站位	Prepare Ribs for loading into Main Assembly Jig 准备进入总装型架的肋板
4-0	Laydown Station 0 架外工位0	Laydown Wing Rotation and Offline Assembly Cell 架外机翼旋转和离线组装单元
4-1	Laydown Station 1 架外工位1	Manual Bolting Cell 手动螺栓紧固单元
4-2	Laydown Station 2 架外工位2	Inspection and Testing Cell 外形检测与气密试验
4-3	Laydown Station 3 架外工位3	Moveables Integration Cell 可动部件整合单元
4-4	Laydown Station 4 架外工位4	Packing and Shipping Cell 包装与发运工位
5-1	INBD Flaps Assembly Station 内襟翼装配站位	INBD Flaps Assembly Jig - Mobile Fixture 内襟翼装配型架 - 可移动工装
5-2	OTBD Flaps Assembly Station 外襟翼装配站位	OTBD Flaps Assembly Jig - Mobile Fixture 外襟翼装配型架 - 可移动工装
5-3	Aileron Assembly Station 副翼装配站位	Aileron Assembly Jig - Mobile Fixture 副翼装配型架 - 可移动工装
5-4	Robot Drilling Station 机器人制孔站位	Robot Drill Skin Panels on Flaps and Ailerons 机器人对襟副翼蒙皮制孔
5-5	Metrology Inspection Station 检测站位	Laser Tracker Inspection 激光跟踪仪检测

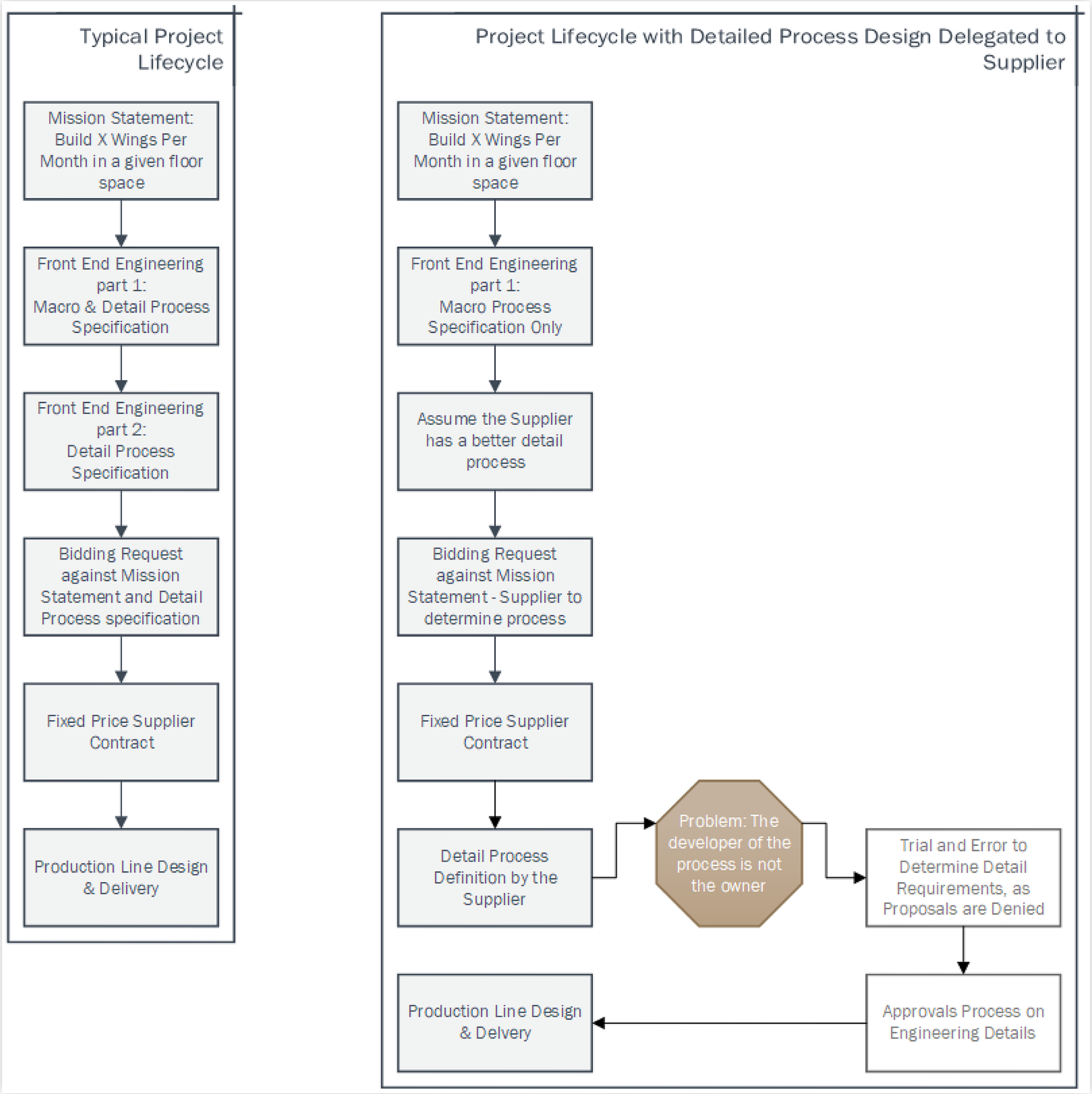
Appendix 2: Factory Stations Layout



Appendix 3: Project Life Cycle Chart

The more typical project flow (on the right) assumes a comparatively greater amount of planning and process design to be done by the customer, prior to the commissioning of the contract.

The project flow experienced in this case (on the left) illustrates the attempt to shift the detailed process design onto the supplier, in the interest of process innovation and risk reduction. This likely results in no real cost or time savings to the customer due to the difficult approvals process that was experienced.



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ISSN 0148-7191