Aircraft Wing Build Philosophy Change through System Pre-Equipping of Major Components

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ABSTRACT

In the civil aircraft industry there is a continuous drive to increase the aircraft production rate, particularly for single aisle aircraft where there is a large backlog of orders. One of the bottlenecks is the wing assembly process which is largely manual due to the complexity of the task and the limited accessibility. The presented work describes a general wing build approach for both structure and systems equipping operations. A modified build philosophy is then proposed, concerned with large component pre-equipping, such as skins, spars or ribs. The approach benefits from an offloading of the systems equipping phase and allowing for higher flexibility to organize the pre-equipping stations as separate entities from the overall production line. Its application is presented in the context of an industrial project focused on selecting feasible system candidates for a fixed wing design, based on assembly consideration risks for tooling, interference and access. Further industrial, human and cost factors are discussed to establish project competiveness. The main findings show a potential to reduce assembly time of systems equipping operations by 30% together with a lower ergonomic impact score. The paper also presents design rules derived from the case study towards a system design for a pre-equipping build philosophy. Primarily, cross component interfaces should be avoided as much as possible. Access for phase one structural operations need to be considered as well as major component jig pickup points. To increase system installation independence, layout considerations of components should lead to sufficient access to all components at any installation stage.

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INTRODUCTION

The definition of a product's assembly line structure heavily influences production rates and cost [1]. Generally speaking a desired production rate is to be achieved at minimal cost, leading to a distribution of assembly tasks to a number of work stations, operating in sequence and parallel. The cycle time for the stations defines the production rate as well as idle time within workstations. Mathematically speaking, this is a form of the well-known Bin Packing Problem [2]. The allocation of such tasks is defined by hard physical precedence constraints, such as requiring a bracket to be fitted before the assembly of a pipe can take place. In addition soft constraints are considered such as how to organize assembly operations effectively, including tooling, infrastructure and worker environment.

In the case of an aircraft, the product is highly complex. A large number of assembly operations are required involving a multitude of hard precedence constraints. Also, parallel operations are much more common since the product is large and physical space is available for operators. With all these sequential and parallel processes the control of an equal balanced work time, also called cycle time, for each station is difficult. Disruptions in a given station will lead to an impact on the overall factory production rate. Hence any changes in build philosophy which are able to reduce such disruptions are desirable. Equipping aircraft components, specifically wings, are also a difficult environment to work in from an ergonomic perspective. Once the wing box is closed, in-tank and in-leading edge work requires operators to hold strenuous and demanding positions [3].

An approach taking within the automotive industry changes the sequential build approach to a modular setup [4]. This modularity comes in form of two aspects. The modular designs allow a common base chassis to host different modules and so form product variation. The assembly line, driven by this modular design allows for increased independent and parallel activities to take place, before modules are joined. Such an assembly line is highly flexible and has the potential to cut production costs significantly [5].

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With large order backlogs for the two major civil aircraft manufacturers in the single aisle aircraft category, improvements in assembly and production techniques are essential [6][7]. Hence this paper focusses on the concept of major component pre-equipping which aims to relieve some of the issues for aircraft assembly time, by moving operations to a separate equipping station before the main production line commences. The station will allow for a controlled environment and an ergonomically improved part orientation. By decoupling the system equipping assembly operations from the linear flow of mostly structural operations, a more modular build philosophy is achieved.

SEQUENTIAL & PRE-EQUIPPING BUILD PHILOSOPHIES

A theoretical production philosophy process is considered for the assembly and equipping of aircraft wings. It consists of two major phases. In the first the structural parts of the wing-box are assembled by mounting spars, ribs and skins in a large fixed jigging structure. Drilling, bolting and sealing are carried out on the stationary wing structure. Phase two moves the closed wing box out of the jig and onto an assembly line. The wing now undergoes further minor structural modifications and tests before the system component installation takes place. The assembly line consists of sequential stations for work to be completed before the wing is moved to the next station at the defined cycle time. Figure 1 shows a simplified representation of such a two phase process and the work content associated with each station. The coloured bars represent the different parallel activities in each assembly station, balanced and terminated at the same cycle time as indicated by the black lines. Alternatively, the wing could be moving continuously along the production line while equipping takes place.

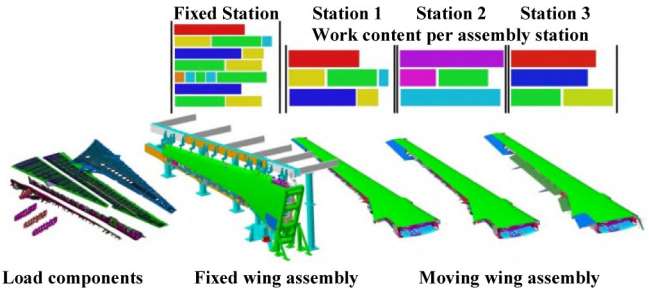


Figure 1. Two phase sequential build philosophy

This arrangement of the wing assembly is essentially a sequential build process. Parts are merged together to produce a larger assembly which is then fitted out with subsequent smaller system parts, one by one until the wing is completed. It benefits from a clear separation between structural (dirty) and system (clean) related tasks. Hence few drilling or fettling takes place after the closed wing-box arrives at the stations for system equipping.

In a second type of assembly philosophy work content is reduced during the late system equipping stations and moved forward to a pre-equipping station dealing with the major wing components. Essentially this extends the total number of bays and hence potentially allows for a reduced cycle time. Fully equipped major components are then loaded into the fixed jigs and the wing box is closed. Final testing and equipping takes place in the moving assembly line in phase two. This process is shown in Figure 2.

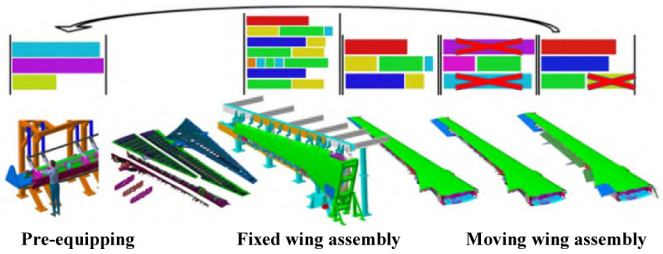


Figure 2. Two phase pre-equipping build philosophy

Alternatively the pre-equipping activities could be offloaded to a tier one OEM supplier directly hence reducing infrastructure, storage and personnel costs. The equipped major components are then supplied directly to the fixed jigs in phase one.

The pre-equipping approach requires substantial system protection, handling and interference considerations. Even though structural and system equipping tasks are still executed separately, the equipped components now need to pass through the whole structural build activities.

METHODOLOGY

This paper proposes a methodology to identify opportunities for offline pre-equipping for a complex system installation process. The procedure includes the following steps:

- Initial feasibility assessment by interfaces
- System location assessment
- Ranking

In the initial feasibility assessment each system is evaluated using two criteria. The first looks at the number of main interface components and the second whether the interfaces, such as mounting brackets, are already present to install the systems. Systems that interface to only one main component and have the interfaces in place are considered to be candidate parts for pre-equipping.

The second step in the methodology is to perform a detailed assessment of the system location of the components taking into account any assembly operations that will be undertaken after the pre-equipping stage. For this stage access to the full CAD assembly of the systems and / or the physical installations is required.

The third step in the methodology is to rank the feasible pre-equipping opportunities. A risk analysis for each feasible system is performed covering access, damage and interface considerations and risk mitigation is identified where possible. The risk level for each feasible system is then scored using a probability-consequence matrix as shown in Table 1. Risk mitigation scores are defined in five levels with the scores scaled based on the level of investment required to mitigate the risk. A third score defines the amount of investigative

work required for each system candidate risk to provide a pre-equipping implementation. The scoring values and their descriptors are given in Table 1.

Table 1. Method ranking criteria

	Indicates a probable occurrence	Indicates very likely occurrence	Indicates an observed occurrence	Indicates a condition by design
Indicates restriction to carry out work. Power tool & equipping within 20cm of system components	1	2	3	4
Indicates significant restriction to carry out work. Power tool/ equipping within 5cm of system/ components	2	4	6	8
Indicates confirmed access & interference restriction. Physical contact/damage possibility visually confirmed	3	6	9	12
Indicates a condition preventing application with the current design	4	8	12	16

Score	2	3	4	10	40
Mitigation	Change in equipping process or tooling usage	Addition of system protection components	Addition & removal of temporal fasteners	Change in Jig & template design	Change in system design

Score	1	2	3
Verification work content	Basic investigation	+ Mock system demonstrator	+ on line trials

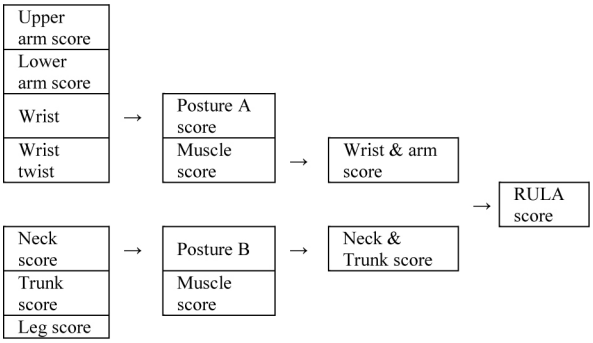
Assembly time savings due to improved operator visibility, reachability and position have been estimated with a combination of two theoretical methods. The two are the classical design for assembly (DFA) approach as presented in [8] and a tool use and acquisition time estimation method (MOST) [9]. Detailed information on the assembly sequence numbering system and the calculation of the time estimates may be consulted in those references. The method breaks assembly operations down into individual steps, assigning statistical time estimates and penalty values for access and visibility. This allows for time reduction estimation if the assembly process changes into a more favourable condition in the pre-equipping philosophy. Some promising results have been shown in the application of these two methods in combination [10].

Next to the assembly time impact, the ergonomic and postural conditions have been studied with the help of the Rapid upper limb assessment (RULA) [12] method and observations on the shop floor. RULA first introduced in the 90s, provides a quick muscle and posture impact overview to screen for operator risks to upper limb disorders. Originally a work sheet method, it is now also available in CAD tools such as CATIA. Table 2 shows the range of scores assigned to each upper body limb. Together they then form a single final score via the process shown in Table 3. Further detail on the RULA method application is available in [11].

Table 2. RULA score ranges per limb

Segment	Score Range	Color associated to the score 1	2	3	4	5	6
Upper arm	1 to 6						
Forearm	1 to 3						
Wrist	1 to 4						
Wrist twist	1 to 2						
Neck	1 to 6						
Trunk	1 to 6						
Muscle	Binary	0	1				

Table 3. RULA scoring process



Finally, the feasible systems can be plotted based on their risk score and the estimated reduction in installation time. The most desirable candidates are those which offer a high time benefit and a low "risk" cost as shown in Figure 3.

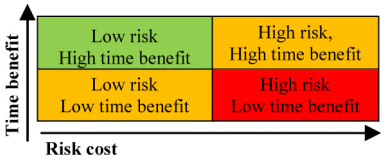


Figure 3. Conceptual view of risk vs cost trade-off

INDUSTRIAL APPLICATION STUDY

The methodology has been applied in a near term change context to assess the pre-equipping philosophy potential of current assembly activities at an aircraft OEM factory. Hence the application study does not allow design modification to the actual aircraft.

Wing System Pre-Equipping Feasibility

Initial feasibility was determined based on the system interfaces to the major components based on a review of the assembly work instructions for the equipping tasks. Systems which connect to multiple components cannot undergo the pre-equipping process.

In addition the fastening interfaces, such as brackets and secondary structures need to be present on the major components to install the system parts. Table 4 presents the initial pre-equipping feasibility for the studied systems.

Table 4. Initial pre-equipping feasibility

System	Main components	Interfaces	Feasibility
Fuel Quantity	Top Skin & Ribs	N	N
Jet pump	Top Skin & Ribs	N	N
Fuel feed	Ribs	N	N
Fuel recirculation	Ribs	N	N
Fuel vent	Ribs	N	N
Fuel spill	Top Skin & Ribs	N	N
Re-fuel	Ribs	N	N
Fire-wire	Leading edge	S	Y
Bleed air ducting	Leading edge	S	Y
Leading edge electrics	Leading edge	Y	Y
Trailing edge electrics	Trailing edge	S	Y
In-tank hydraulics	Top Skin, Ribs	N	N
Generator cables	Leading edge	S	Y

*N – No, S – Some, Y - Yes

The investigation eliminated most wing tank internal systems as being unsuitable, since the tubing passes and connects through multiple ribs. Remaining are the leading and trailing edge systems (LE, TE) which have some or all their fastening interfaces present on the supplied LE and TE components. Based on the initial assessment five systems were considered as candidates for pre-equipping.

Detailed Assessment

Following the identification of candidate systems each feasible system underwent a detailed assessment and risk analysis, by comparing the system component locations to all other wing assembly operations in the vicinity. Common structural related operations include drilling, skin fettling, bolt installation, painting and sealant applications. Since the pre-equipped components pass through the fixed jig in phase one, the system location needs to be checked against the structural drilling, bolting and sealing activities required to close the wing-box.

Figure 4 shows the typical location of the electrical, bleed air and fire-wire system components on the front spar and leading edge D-nose. Two typical D-nose rib sections are also shown, where the systems pass through the D-nose ribs at the slat tracks.

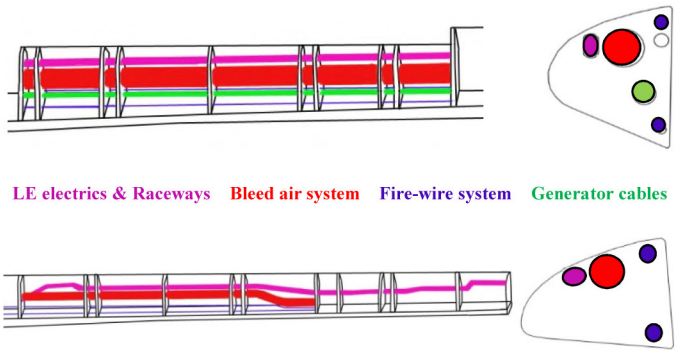


Figure 4. Leading edge system locations

The electric harness is housed in raceways which connect to the D-nose skin with brackets. The raceways consist of multiple straight and cornered pieces forming a multi-channel to house separate cable bundles of the harness. Generally speaking the raceway track stays towards the rounded tip of the D-nose skin with a large clearance to the front spar. The bleed air duct on the other hand is located closer to the spar, at the centre of the D-nose ribs. The larger tube runs from the engine pylon towards the cabin, where as a smaller duct provides bleed air to the outer parts of the wing. Further outboard the tube also changes position and lies even closer to the upper edge of the front spar. The generator cables together with the fire-wire cables are the closest to the spar. They are held by clips or cable blocks, bolted to brackets on the spar. The generator cables are only present inboard to provide electrical power from the pylon to the cabin. The fire-wire cables cover the surroundings of the bleed air ducts, to alert of high temperatures. Pairs of cables run close to the upper and lower edge of the front spars, weaving around the pylon areas and connecting to the raceway harness.

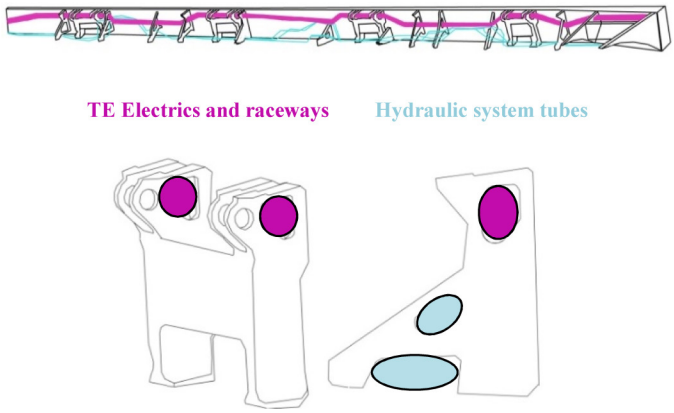


Figure 5. Trailing edge system location

Figure 5 shows a partial rear spar, its structure and system components. Again the raceway channels house the electrical harness. It is generally located in the middle of the spar, but also changes location towards the upper spar edge when an actuator hinges is encountered. The location of the hydraulic tubing is variable, but generally stays towards the lower edge of the spar. The pipes are fitted to clamp blocks, which bolt to the structure hinges and ribs.

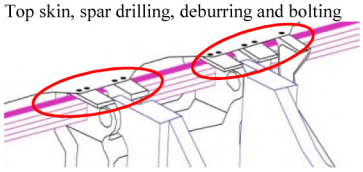
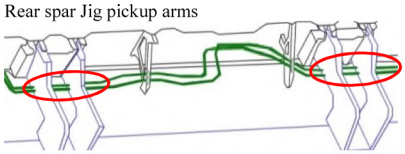
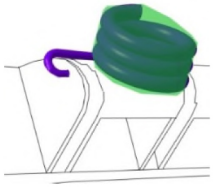
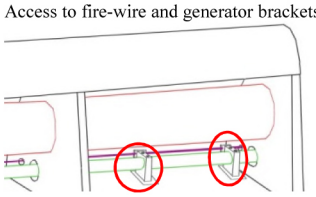
The trailing edge systems main risks are present during the closure of the wing box. The rear spar is fixed in jigs and held by various pickups. Since the hydraulic tubes are not very well defined in position and fixed at a distance from the spar, significant interference with the jigging structures are present. The pipework also overhangs the raceways in some locations, making raceway installation a precedent for hydraulic system installation.

The raceways with installed harness are at high risk to drill strike at the top edge of the rear spar. The top skin is drilled off and bolted to the rear spar. Each drilled hole also requires access from both sides for deburring operations. Raceway walls are often very close to the top skin at the actuator hinge areas. The highest priority issues identified per pre-equipping candidate are shown in Table 5.

Systems located in the D-nose component also produce access and interface issues. The brackets required for the lower pair of the fire-wire cables are not present on the supplied major component. These brackets are part of the butt strap panels fitted to the bottom

skin overhang. Sealing activities on the front spar and top skin edge are also restricted due to the upper fire-wire cables. The generator cables pose only limited access problems since they are well located towards the centre of the spar. However some of their structural brackets are also not present on the supplied D-nose. The leading edge electric system has the fewest restrictions. Its location in the front of the D-nose gives it a safe distance from any skin to spar drilling taking place in the fixed jigs.

Table 5. High priority pre-equipping issues

System	Risks	Mitigation
Trailing edge electrics	Top skin, spar drilling, deburring and bolting 	Redesign
Trailing edge hydraulics	Rear spar Jig pickup arms 	Tooling modification
Leading edge electrics	Harness coil storage and protection 	Protective container
Bleed air ducting	Access to fire-wire and generator brackets 	Change in assembly procedure
Fire-wire cables	Bracket interface not present	Redesign
Generator cables	Bracket interface not present	Pre-equip with bracket

The harness however is a large single cable assembly, which is coiled up at the raceway ends for later wing to fuselage assembly. These cable coils need to be protected and processed through the wing structural operations. Issues with the bleed air duct are again the drilling operations at the top skin, spar interface. In addition the large duct restricts access to the generator and fire-wire brackets.

In addition the fixed jig requires the D-nose to be fixed with pinned arm interfaces, similar to the trailing edge. The two connection points per connecting arm are within the D-nose. Hence the systems need to be clear of this arm, to allow D-nose loading and removal from the jig.

A collection and ranking of the system candidates against the assembly risks was conducted in collaboration with factory workers, equipping manuals and observational work. The scoring included probability - consequence matrix, a mitigation score and a verification work score as previously described

The resulting trade-off graph for the feasible systems identified in the interface analysis against the risk scores assigned to a multitude of interference, access and tooling issues is shown in Figure 6. The normalized time values show the degree of impact a movement of a system candidate to a pre-equipping area would have. The total risk cost is a normalized summation of the three scoring metrics described in Table 1. The leading edge electrics and bleed air systems emerge as the best trade-off candidates. Hence they were selected to undergo detailed benefit investigations.

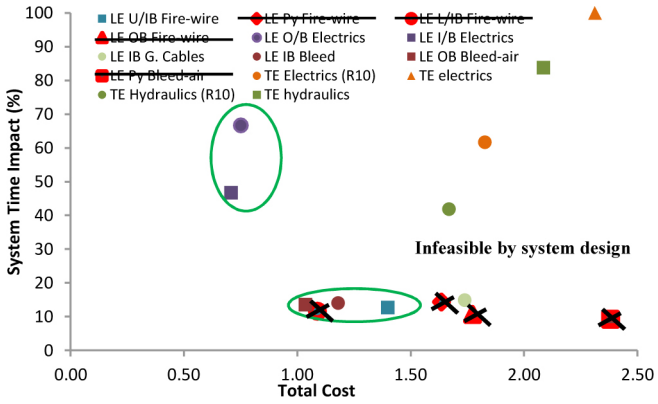


Figure 6. Trade-off between high time impact and risk score

Pre-Equipping Benefits

The trade-off against the risks in Figure 6, are the expected savings in assembly time, the reduced disruption times and flexibility in defining the pre-equipping station without impacting the main assembly line. The most beneficial selections are the leading edge electric and bleed air systems. In order to detail their time reduction potential the DFA/ MOST method was applied. It utilizes standard operation manuals for factory equipping processes and breaks them down into subtasks as shown in Table 6. Only a small sample was chosen for the analysis and taken as a representative activity for the overall process. It shows the installation of a bleed air duct in the leading edge location. The individual action steps are shown, their corresponding time estimates and the changes expected for a similar operation in a pre-equipping environment. A total reduction of ~ 30% is estimated due to access and visibility improvements. This reduction time forms the budget against which any pre-equipping costs have to be offset. Current investment costs include protection equipment, infrastructure costs of the pre-equipping station and assembly time increases due to protection fitting and removal.

Next to the assembly time impact, the ergonomic and postural conditions have been studied with the help of the RULA [12] method and observations on the shop floor. Hence common operator positions for D-nose equipping in the current build process and an estimated process in the pre-equipping station have been generated and are

visualized in Figure 7 & Figure 8. The resulting scores of these positions were then produced in CATIA's ergonomics workbench and are given in Table 7.

Table 6. Equipping time reduction estimation for bleed air duct

ID		DFA/MOST Code [8],[9]	Quantity	Time (%)	Changes	Time reduction (%)
1	Get components Blast tube x1, Rivets, sealant	A10,B3,G 3,A10,B3, P1	2	5.3		0.0
2	Obtain tools. Riveter, brush, marker	A10,B3,G 3,A10,B3, P1	1	2.7		0.0
3	Check hole quality conforms to standard	A1,B3,G1, T3,P1	1	0.8		0.0
4	Handle and trail fit blast tube	HC = 3,9 & IC = 6,2	1	3.1	IC 6,2 to IC 6,0 Part and location reached easily	32.0
5	Handle and slave fasten bolts	HC = 0,1; IC=9,2	3	8.9	IC 9,2 to IC 9,0 Part and location reached easily	25.0
6	Mark area of bolts on structure	A3,B10,R3 ,B10,A3	3	7.7	B10 -> B3 Simple bend	48.2
7	Handle and unfasten slave bolts	HC = 0,1; IC=9,2	3	9.6	IC 6,2 to IC 6,0 Part and location reached easily	30.8
8	Handle and remove blast tube	HC = 3,9 & IC = 6,2	1	3.1	IC 9,2 to IC 9,0 Part and location reached easily	32.0
9	Lightly abrade locations on structure	A6,B10,G 1,S1,B10, A6	3	9.1	B10 -> B3 Simple bend	41.1
10	Lightly abrade blast tube	A10,B3,G 3,S1,B3,P3 ,A10	3	8.8		0.0
11	Apply sealant to position on blast tube	A6,B3,G3, S1,B3,A6	3	5.9		0.0
12	Position blast tube and align with holes	HC = 3,9 & IC = 6,2	1	3.1	IC 6,2 to IC 6,0 Part and location reached easily	32.0
13	Handle and insert Rivets	HC = 0,1; IC=9,2	3	8.9	IC 9,2 to IC 9,0 Part and location reached easily	25.0
14	Rivet fasten	A6,B10,G 1,F3,A3,B 10,P1	3	9.1	B10 -> B3 Simple bend	41.1
15	Apply sealant to IB and OB of blast tube to rib edge	A6,B10,G 1,S10,T16, A6,B10,P1	2	10.7	B10 - B3, T16 to T6 (less checking)	40.0
16	Handle and insert duct tube	HC = 7,9 & IC = 6,2	1	3.2	IC 6,2 to IC 6,0 Part and location reached easily	19.2
Total time reduction: 28%						

Even though the pre-equipping station working conditions have only been studied conceptually the results show an improved operator ergonomic environment.

The initial score of 7, according to RULA guidelines warranting an immediate investigation into posture changes, is reduced to 4 in the pre-equipping case. Changes in postures will be required to cover different system equipping activities, hence further work is required to establish potentially worse postures encountered.

Table 7. RULA scores for equipping scenarios

Position part	As-is Equipping Score	Pre-equipping Score
Upper Arm	4	3
Forearm	1	3
Wrist	2	3
Wrist Twist	1	1
Posture A	4	4
Muscle	1	1
Wrist and Arm	**5**	**5**
Neck	4	1
Trunk	1	2
Leg	1	1
Posture B	5	2
Neck, trunk and leg	**6**	**3**
Final Score	**7**	**4**

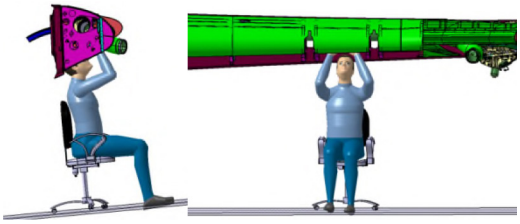


Figure 7. As-is equipping

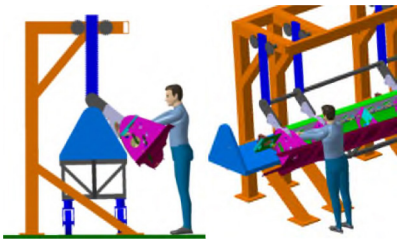


Figure 8. Pre-equipping

SYSTEM DESIGN IMPACT

The industrial application study of the pre-equipping build philosophy to wing systems highlighted a number of issues which eliminated candidates in their current design. This section collects such system design related "showstoppers" and proposes re-design options to present a future orientated vision that would enable the majority of leading and trailing edge systems to be pre-equipped.

System Location and Interface Re-Design

System candidates eliminated due to their structural interface designs included the fire-wire system and various in-tank fuel systems. In-tank systems have an inherent difficulty for being suitable for the pre-equipping philosophy, since they usually cross multiple ribs and skins with tubing, connectors and valves.

There may be scope for systems mostly fastened to the top or bottom skin, if rib-crossings are suitable re-designed to allow for rib installation after cross skin tubes have been installed. Figure 9 gives two examples of typical rib crossings. The fuel pipe crossings are often located centrally in the rib and unlikely to be suitable for pre-equipping. The hydraulic tubing is fixed to the skin with brackets and clamps, passing through the ribs close to the skin with grommets, bushes or pipe fittings.

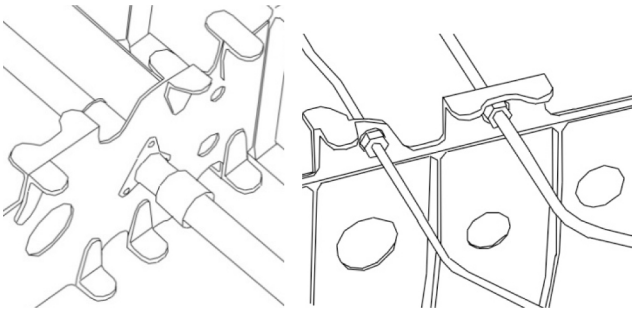


Figure 9. Typical in-tank fuel and hydraulic tube rib crossings

Pipe fittings, which don't allow pipe sliding through ribs will not allow for total system pre-equipping. However with suitable rib redesign large sections of the system may be installed to the skin. A typical hydraulic pipe arrangement with fastening interfaces is shown in Figure 10. These components between rib pipe fittings can be installed to the skin without ribs present.

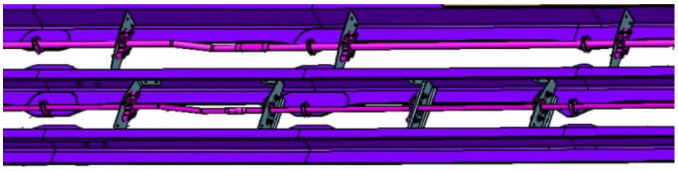


Figure 10. Pre-equipped hydraulic pipes to bottom skin

A possible modification to the ribs is shown in Figure 11. The rib is lowered onto the skin, with the cut-outs providing the space for the pipes to be inserted. The pipe bushings are then fastened and split grommets installed if required. The cut-out may also be closed by an additional bracket if required.

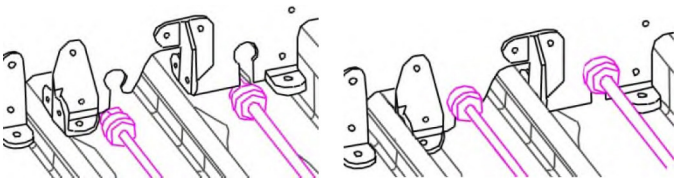


Figure 11. Modified rib with hydraulic tubes pre-equipped to bottom skin

Raceways at the trailing edge are required to have sufficient clearance to the top and bottom skin, as well as any secondary trailing edge rib structures, such as brackets and riblets. Major issues encountered during pre-equipping showed drilling, spot facing and deburring activities at these structural parts need to be taken into consideration during design. Ideally the raceways should be routed in the centre of the spar. However due to large structural components such as spoiler and aileron brackets, this is not an easy task to achieve.

The trailing edge hydraulics system consists of high pressure pipes located to brackets and clamp blocks at the rear spar. The pipe layout is determined by the location of the actuators, system separation rules and interface structural integrity. Ideally the pipe layout should be independent from the electrics raceways; however with little available spar area this may not be possible. The dependency will induce an installation order, requiring raceways to be installed before pipes. In addition to these systems layout considerations the phase one structural jig design will have to accommodate the pre-equipping rear spar structure. Typical systems locations are shown in Figure 12.

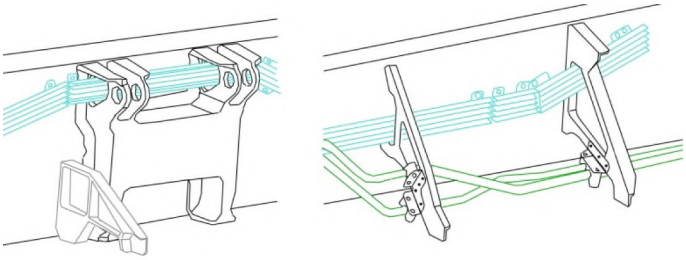


Figure 12. TE bracket, raceway and hydraulic tubing location

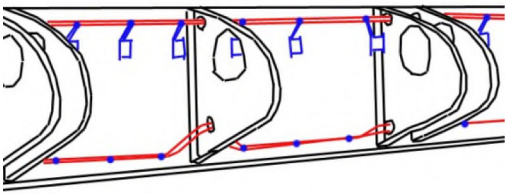


Figure 13. LE Fire-wire location and brackets

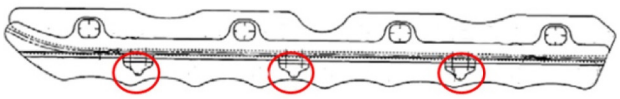


Figure 14. Bracket location on bottom skin packers

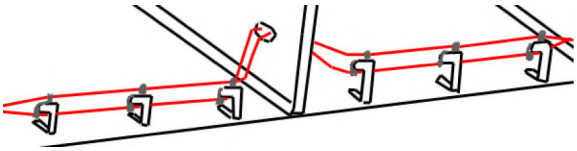


Figure 15. Bracket redesign to interface with front spar only

The leading edge systems locations would require re-design of brackets for the fire-wire and generator cables. All bracketry should be installed to the front spar, rather than interface to secondary structures such as wing butt-straps and packers. These are only installed after the skin is located and hence prevents pre-equipping. Examples of a bottom skin packer and a typical fire-wire arrangement are shown in Figure 13 and Figure 14. An alternative design is proposed in Figure 15. The cable clips are now mounted on brackets directly fixed to front spar. This enables this system to become a feasible pre-equipping candidate, undergo detailed damage and tooling impact analysis and add to the overall pre-equipping time savings scope.

SUMMARY/CONCLUSIONS

The industrial study determined currently feasible pre-equipping system candidates and the changes required to make others possible. Systems fulfilling interface and access feasibility for a current wing include the leading edge electric and bleed air systems. Theoretical time and ergonomic assessments showed pre-equipping of such

systems can lead to a reduction in assembly time of around 30% and RULA score by 3. Further work is planned to experimentally confirm such results with a wing leading edge demonstrator.

For other non-feasible candidates a number of possible re-design options have been presented. Changes range from small scale bracket modifications to hold systems directly on the spar, to larger scale structural and layout changes. From these, Table 8 presents a summary of the design guidelines for a pre-equipping wing build philosophy. There is an opportunity to make substantial time savings to the systems equipping on future wings if the wing is designed with regards to these pre-equipping guidelines.

Table 8. Pre-equipping design guidelines

Design Guideline	Objective
System fastening interface to only one major structural component	Pre-equip the system to a single components
System layout to allow access to other systems in its vicinity	Pre-equip the system independently of other systems installation state
Wing box jig to accommodate pre-equipped components	Locate the equipped components within tolerance to complete the wing box in a jig
Clearance, protection and separation of secondary structure work from system components	Operator access is required to spar and skin interfaces

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DEFINITIONS/ABBREVIATIONS

LE - Leading edge

TE - Trailing edge

I/B - Inboard of Pylon

O/B - Outboard of Pylon

OEM - Original equipment manufacturer

DFA - Design for assembly

MOST - Maynard operational sequence technique

RULA - Rapid upper limb analysis

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Aircraft wing build philosophy change through system pre-equipping of major components

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