A Systems Engineering Framework that Integrates Aircraft Final Assembly Design Activities

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Abstract. A modern large-scaled aircraft consists of numerous structural and system components. Many of those components are installed and tested in the final assembly stage. To design the aircraft final assembly processes, engineers are required to have a comprehensive understanding of the interdependences and interactions between all the aircraft components, and the following influence to manufacturing operations. This work is difficult and challenging due to final assembly design activities lie in both product design and operations management fields. Final assembly processes link to product and operations constraints, thus a process-oriented method is required. Aircraft as a typical system of systems, systems engineering framework, for instance the V model, is used to understand the product complicities and guide the product design activities. However, there is no such a framework for final assembly line (FAL) process. This research investigates the activities of aircraft integrations at final assembly stage, then introduces a framework following Systems Engineering (SE) principles for integrating FAL design activities.

Keywords: Aircraft final assembly, Complex systems, Framework, FAL Design activities.

1 Introduction

The definition of aircraft final assembly varies from the aircraft types and manufacturing strategies. However, A general scope of aircraft final assembly can be defined by working contents since early 1950s, which include major structural sections mating, airframe systems installations and functional tests[1–3]. An aircraft final assembly process represents the integration process of aircraft component, sub-system, systems, major systems, and the overall aircraft in a production system. Modern advanced civil and transport aircraft contain new functionalities to satisfy comfortable, efficiency and safety requirement. As a result of that, aircraft systems are becoming more integrated and coupled with more interdependences and interactions. It is reported by aircraft industry that the validation parameters of an aircraft system are raised from 0 in 1920s to 1,000,000 in 2010s[4]. This design change asks for more complicated functional tests processes in the final assembly line (FAL). The FAL overall processes are not simply installations with continuity tests, but with a series of factory level functional tests. Designing a modern aircraft final assembly process is now more challenging. Since final assembly process connects product and operations requirements, this research will concentrate on the methods and approaches used for final assembly process generation, then try to propose a new method for process engineers to ease the difficulty.

2 Literature Review

This section investigates the final assembly design activities first, and reviews the methods used for process generation. Research gaps are concluded to help the new method development later.

2.1 Aircraft Final Assembly

Assembly is the process of putting together a number of parts to make a machine or other product[5]. Aircraft assembly means "the airplane grows from small assemblies, and these small assemblies are made as complete as possible before moving on to the next stage"[1]. Beside this physical-connection-based definition, FAL includes the components and sub-assemblies being processing, the installations and tests processes, and associated tooling and facilities. These contents are known as product-processes-resources (PPR)[6], which are the objectives for final assembly design. Based on the PPR concept, it is clear that final assembly design lies in two fields, aircraft product design engineering and operations management. As mentioned before in the introduction section, many of the aircraft systems changes contribute to the difficulties in modern aircraft final assembly design. Systems integrations at final assembly stage and their associated operations, as well as system tests are identified as the scope of this research.

2.2 Systems Integration at Aircraft Final Assembly Stage

Ashmead describes Douglas A-4 aircraft final assembly process as "hardware, lines, etc., are placed, tested, and checked out whenever possible in the smaller assemblies, so that when these components meet the next larger assembly much of the interior work is done"[1]. Frankenberger states A320 FAL package includes insulation blanket layout, windows and doors installation, electrical cable wiring, mechanical system lines layout, and different kind of system tests[7]. Figure 1 shows the systems installations in aircraft forward-fuselage section and the overall final assembly process.

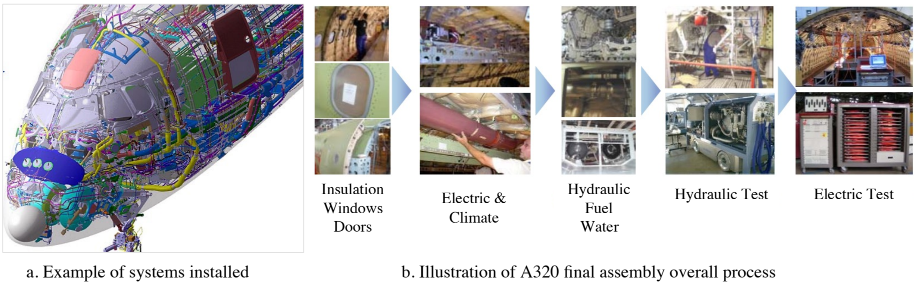


Fig. 1. The complexities of aircraft systems and final assembly process [7]

Figure 1 illustrates the A320 FAL overall process from brackets and fixed components on the structure, to pipelines and cable harnesses and functional verification tests. From systems integration aspect, it also explains the general final assembly process is from physical installations to functional tests. This clarifies the product status being assembled in an assembly line, and the major stages of integration processes. When considering process associated resources, the overall process can be arranged in a station-by-station with count-down numbers pulsed-line or flow-line layout in figure 2.

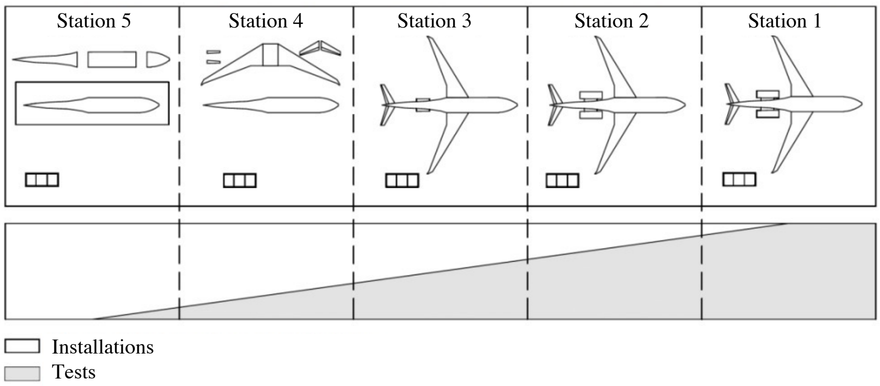
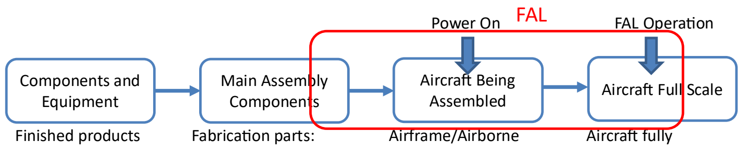


Fig. 2. Aircraft FAL process in a station-by-station flow-line layout [8]

It can be seen from figure 1b and figure 2 that physical installation tasks are reducing from station 5 to 1. By contrast, test tasks are growing as FAL process goes. It is important to know that a modern aircraft FAL not only presents how components and equipment are installed to build the final product geometry, but also whether the functions are integrated properly. To achieve this, FAL tests are arranged to check and verify the installation quality.

There are different kinds of test in the aircraft design and manufacturing process. Doumbia et al. and Plankl introduce the system test sequence in Airbus, which consists of the tests in specialised test labs, tests on aircraft at manufacturing and FAL stage [9, 10]. In Boeing's streamlined final assembly, a series of factory level integration tests, including the manual wire pin-to-pin continuity test, system built-in test and factory functional test (FFT) are used to ensure the correctness of system installation and functionalities [11, 12]. To conclude, the test activities can be shown in figure 3 in terms of products, test type, test tools, test occasions and who will be in charge of these tests.



Products	Finished products from supplier	Fabrication parts: Pipes, Cable Harness	Airframe/Airborne systems partly installed	Aircraft fully equipped
Test Type	Tests on electrical assemblies • Wiring continuity tests	Tests on sub-assembly system • Wiring and mechanical continuity tests	Tests on main assembly system • Full continuity tests • Functional tests	Tests on aircraft • Static Tests • Running Tests
Test Tools	Test benches and specific tools	Test benches and specific tools	Manually test (signals) Automatic test bench	Manually test (operations) Automatic test bench
Test Occasions	Before sub-assembly lines	Before final assembly lines	Factory level ground tests on final assembly lines	• Final tests on final assembly lines • Outdoor ground test
Tested by	• Suppliers • Main manufacturer	• Suppliers • Fabrication plants • Sub-assembly plants	Final assembly plant	• Final assembly plant • Flight test department

Fig. 3. Summary of aircraft system tests in the assembly integration process

Compared to the mechanical tests for structural assembly such as fuselage alignment and fuel tank airtightness test, the summary indicates that a modern advanced aircraft system test process is actually the process of software applications on aircraft systems [13]. It is due to the fact that most of the advanced aircraft systems are powered by real-time digital control computers today. Figure 3 also shows the FAL scope in the systems overall integration map, which focuses more on the full continuity and functional test for the verifications of sub-system, system, major system, and aircraft.

2.3 Methods for FAL Process Generation

Assembly sequence planning (ASP) is the design activity to arrange and determine the assembly process following certain sequencing principles [14]. The results of ASP include specific sequencing or precedence requirements in that assembly tasks must precede other tasks [15]. It is concluded by Scallan that product design characteristics and manufacturing operations are two planning concerns in ASP [16].

On product design characteristics aspect, there are absolute constraints and optimization constraints, or known as strong constrains and weak constraints [14, 17, 18]. Violating the absolute or strong constraints will lead to infeasible assembly sequence, while violating an optimization constraint will only cause lower assembly performance [14, 19]. Based on these definitions, people try to develop algorithms for automatic ASP, such as the liaison diagram method, "AND/OR graph", graph-theoretic assembly decomposition method, and assembly tiers method. However, these methods are all strongly relying on physical contact information. Due to many aircraft pipelines, cable harnesses and equipment in a bay do not have direct physical contact, these methods are not appropriate for system sequence generation. This has been admitted by Whitney and Jefferson that in assembly precedence problem the methods for mechanical issues are not suitable for the sequence precedence with other functional components [20, 21]. It is found RFLP (Requirements-Functional-Logical-Physical) method be used to generate an initial aircraft integration sequence towards the realizations of system functionalities, but without simulations and operations verifications integrated [22].

On manufacturing operations aspect, the methods found are mostly from lean manufacturing, including Just in Time (JIT), one-piece flow, standardized working, and continual improvement. Lean manufacturing aims to reduce waste and improve production performance like throughput, line balancing, supply chain and operation cost. It assume that “there is a competently designed assembly ready to be assembled” [21]. Assembly line balancing (ALB) also requires an existing or candidate process. Ríos, Mas and Menéndez comments the lean manufacturing tools that FAL process relates more to the technological criteria than to manufacturing operation parameters [23], thus they cannot be applied to initial FAL process generation.

2.4 Gap Summary

Aircraft industry acknowledged the complexities in designing FAL, and most of those complexities are from the changes in systems integration and technical constraints. Aircraft as a complex product, its FAL process is not only involved in the product functionalities realizations but also in the complex production system. FAL process generation is crucial for FAL design as it connects product design and manufacturing. Previous ASP methods do not resolve modern aircraft FAL sequence generation problem towards neither on technology and operations precedence nor on physical and functional integration. FAL processes are not well integrated with other associated activities such as assembly layout, major resources allocation, and assembly operations planning, because they are all interconnected.

3 Method Development

The research gap investigated in section 2.4 indicates that the airframe systems contribute much of the complexities to FAL design. FAL overall process should firstly satisfy the absolute constraints from system interdependencies, then allocates to final assembly operations. Therefore, the developing method:

- Should cover the FAL design activities along with aircraft lifecycle.
- Should be a structural framework method following the systems integration path firstly.
- Should be a process oriented and centralized method.

- Should allow FAL design associated activities like assembly layout, operations planning to be integrated and linked by verifications.

3.1 FAL Roles in Systems Integration Lifecycle

If examining FAL in the aircraft lifecycle from the systems integration view, it is interesting to find the aircraft airframe systems and avionics finally integrated in FAL are actually linked to simulation model, software integration, initial components integration, and MRO (Maintenance, Repair and Overhaul) units with different level of verifications and validations (see figure 4).

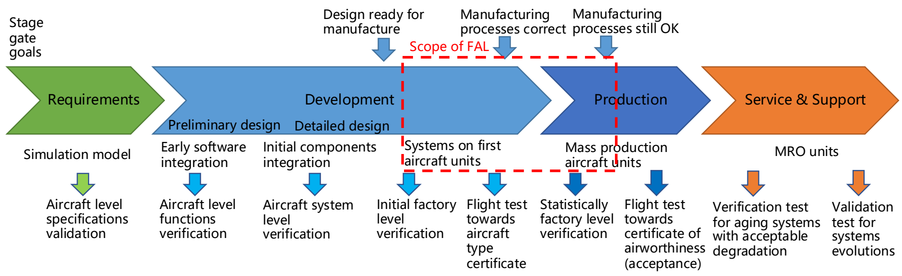
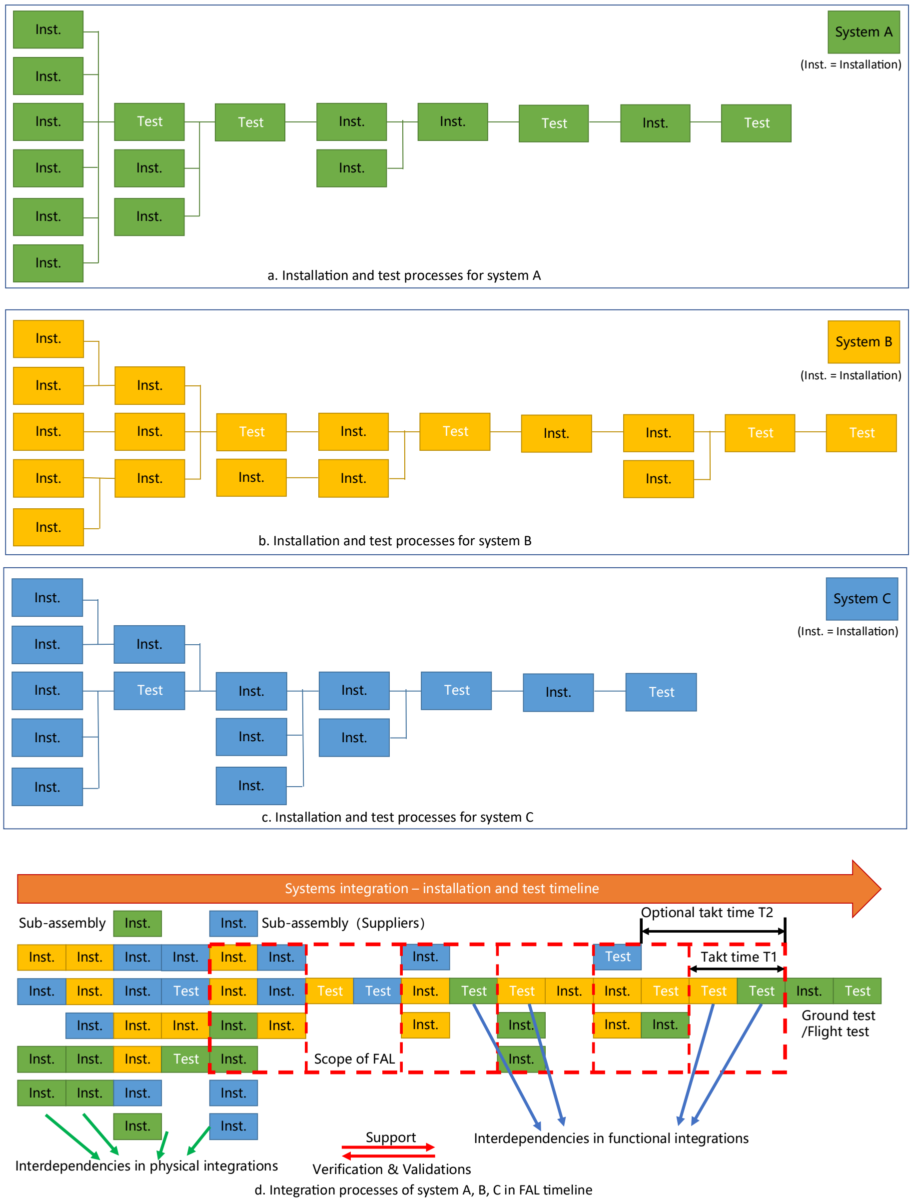


Fig. 4. FAL scope and systems integration in aircraft lifecycle

As all the stages are connected, a weakness during production may be related to system design. A failure in service may be due to poor design or to a lack of sufficient verification tests during development or production. To resolve this issue, different stage gate goals are set following basic systems engineering principles[24]. At detailed design stage, when finishing the initial components integration by system level verification, the goal is ready for manufacture. When the systems are first time installed in an aircraft be processing in FAL, the goal is ensuring manufacturing processes correct. When it comes to mass production with statistically tests as mentioned earlier in figure 3, the goal is ensuring manufacturing processes still correct. In this lifecycle, time and costs are strongly connected, which means if do not apply to it more reworks have to be included in the project.

3.2 Multi-systems Integration in FAL

System of systems is the typical characteristic in FAL integrations. Although the installation and test precedence of one system seems to be fixed, when multi-systems are integrated together, the overall precedence is actually very different. Figure 5 explains this with three systems A, B and C. In figure 5a, 5b and 5c there are installation and test precedence of each system. The precedence of every single system is fixed. But when putting them in the FAL timeline, the overall precedence is changed dramatically. The integrations of one system require additional installations and tests from other two systems (see figure 5d). The complicated interrelationship in the three systems indicate both physical and functional interdependencies should be generated from one system and multi-systems.



a. Installation and test processes for system A

b. Installation and test processes for system B

c. Installation and test processes for system C

d. Integration processes of system A, B, C in FAL timeline

Fig. 5. Example of multi-system integration in FAL

Figure 5d also shows the operations integration in FAL timeline. The dotted red line defines the scope of FAL, and the installations and tests outside this line are sub-assemblies, supplier assemblies, and ground test/flight test. More dotted red lines in the FAL indicate the assembly station works with takt time. Takt time can be redefined with improvement and optimizations in later stage process planning or assembly line balancing. As aircraft system functions follow the path of assembly in integration [25], the processes illustrated in figure 5d should guarantee the correct installation of systems components, such as electrical, hydraulic, and mechanical systems. It should also guarantee the correct operation of systems installed on the complete aircraft.

3.3 Proposed Framework

The inputs of FAL process planning include the information from 3D solid assembly models, and the information from 2D block system schematic[8], which represent the physical and functional integration respectively. Based on figure 4 and 5d, the tests act as stage gates in the overall process. In other words, if tests are determined first, FAL overall process representing in test precedence is then determined [22]. The next step should consider the sequencing of associated physical installations to those tests in zones or bays. After the first two steps, product information is transformed into a work breakdown structure (WBS) in the terms of tests and installations, and initial processes associated design activities such as initial process layout and major facilities allocation can be taken place then. The third step is operations planning towards detailed assembly operations by assembly workers or assembly robots. When linking the design and verifications activities with different design stages in the lifecycle, a proposed framework method can be created in a V model shown in figure 6.

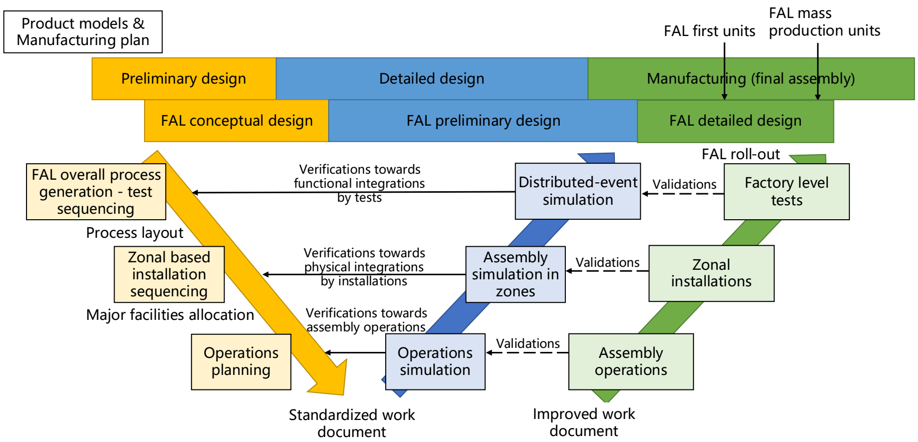
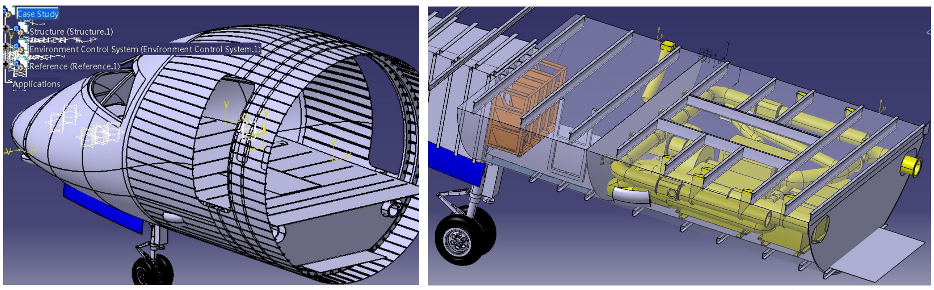


Fig. 6. The proposed framework for FAL design activities

The framework consists of FAL design lifecycle in parallel with product lifecycle, the top-down FAL design activities, and two bottom-up flows with simulations and real-world FAL production activities. These FAL design activities are arranged in V model levels and towards different verifications and validations, allowing a structural information exchange and design iterations. It should be pointed out this framework would be used both for FAL stages towards first units and mass production units. The difference is FAL at early first units stage that the method concentrates more on simulation-based design activities, while at later mass production stage it considers more on real production data-based improvements. The proposed framework generates the FAL overall sequence precedence based on aircraft functional and physical interdependences, which is considered as absolute constraints, priority to operations requirements. In this framework operations planning results are treated more as examiners to the initial process generated and allow design verification loops. This means FAL assembly operations will not lead to infeasible sequence against the realizations of system functionalities, but still have the capacity on optimization of sub-assembly sequences and resources.

4 Framework Implementation

The proposed framework supports FAL design activities from conceptual to detailed stage. This section will use a simplified case to explain the implementation at early FAL design stage towards integration of first units. A solid 3D assembly master model is introduced including an aircraft forward-fuselage section and environmental control system (ECS) components (see figure 7). As the case study model is simplified for illustrating the implementation steps, models only include structural assembly models of the forward-fuselage section, air supply sub-system components, and air conditioning sub-system components in the ECS bay (see table 1).



a. Forward-fuselage section

b. ECS components in ECS bay under floor
(shown without other structure)

Fig. 7. Simplified case study in 3D assembly master model

Table 1. Product Breakdown Structure of the simplified Models

System	Sub-system	Content
Structure	Forward-fuselage	Forward-Landing gear, cockpit, ECS bay, floors (panels), doors, skins.
ECS	Air supply	Shut-off valve, ram air intake pipes, bleed air pipes.
	Air conditioning	ECS packs (pre-cooler, heat exchanger, etc,), air distribution pipes, non-return valve.

The implementation of this case study can be outlined as the following steps shown in figure 8:

- Step 1: prepare the assembly models and system schematics. Extract the high-level ECS functional interdependencies from schematics as absolute constrains, then plan the initial test processes of ECS using system functional deploy and transfer approach [8, 22] (see results in step 1 of figure 8). This step outputs the overall process arranged by test tasks and allows further planning of an initial FAL layout.
- Step 2: plan the installation tasks by allocating test required physical components. Sort the sequence and create sequence options towards possible DFA principles or project requirements (see two sequence options in step 2 of figure 8). The difference between the two options is the ocassion for floor installation, which means whether ECS sub-system components using the access panel on the floor. After the option planning, major facility allocation is a possible FAL design activity in step 2.
- Step 3: outline the detailed and standardized instructions towards assembly and test operations (see instruction example in step 3 of figure 8).

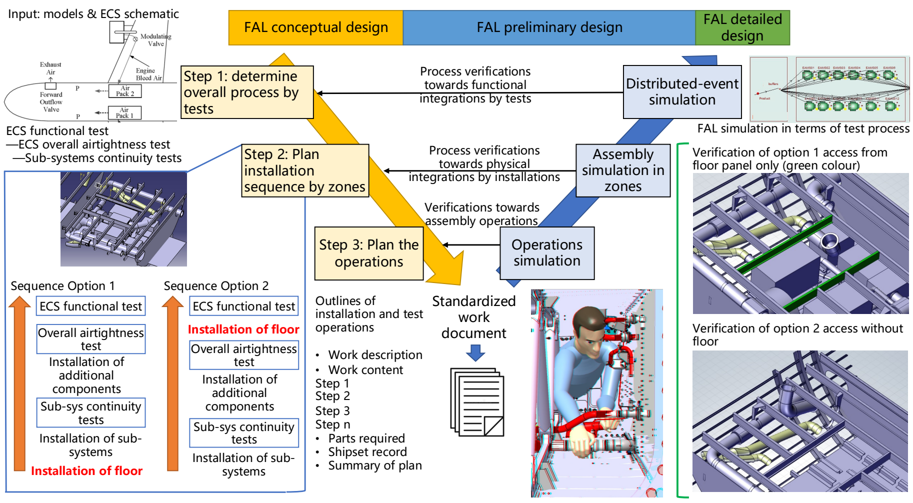


Fig. 8. Framework implementation steps for FAL first units

It is recommended in the three steps that verifications should be involved in time. Although simulation activities are arranged in the bottom-up process, to allow a top-down step move, each step includes general calculation, analysis, or simulation as well. Simulation activities in the bottom-up process are the final verifications with preliminary design results or candidate solutions. This will ensure more design certainty and all the FAL design results are finally satisfied. After a complete design and verification loop is finished, it is possible to rerun once or serval times of the V model process if project allowed or additional requirements required.

5 Conclusion and future work

This research investigates into the characteristics of FAL design activities. A FAL process acts as a bridge to link product design information and manufacturing operations requirements. According to the literature review, gaps are found in the field of ASP. Specifically, they are the lack of a functional-integration-based sequence generation approach, and the lack of a structural-based framework to help understand FAL design activities, thus ease the difficulties in FAL engineering. The proposed framework is developed following basic SE principles which allows FAL design steps be taken in multi-levels with associated design result verifications. As the method intends to cover aircraft lifecycle both for FAL early units and mass production units, the future work will include using a full-scaled aircraft structure and system master model to examine the framework method, and applying it on models or real-world aircraft with more interactions at mass production stage.

Acknowledgements

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