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Using Requirement-Functional-Logical-Physical models to support early assembly process planning for complex aircraft systems integration

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Abstract

The assembly line process planning connects product design and manufacturing through translating design information to assembly integration sequence. The assembly integration sequence defines the aircraft system components installation and test precedence of an assembly process. This activity is part of the complex systems integration and verification process from a systems engineering view. In this paper, the complexity of modern aircraft is defined by classifying aircraft system interactions in terms of energy flow, information data, control signals and physical connections. At the early conceptual design phase of assembly line planning, the priority task is to understand these product complexities, and generate the installation and test sequence that satisfies the designed system function and meet design requirements. This research proposes a novel method for initial assembly process planning that accounts for both physical and functional integrations. The method defines aircraft system interactions by using systems engineering concepts based on traceable RFLP (Requirement, Functional, Logical and Physical) models and generate the assembly integration sequence through a structured approach. The proposed method is implemented in an industrial software environment, and tested in a case study. The result shows the feasibility and potential benefits of the proposed method.

Keywords: Aircraft system assembly, Assembly process planning; Complex systems integration; RFLP modelling

1. Introduction

The system components integrated in modern large scale aircraft are a typical example of complex systems [1], and normally include a large number of equipment, pipes, wire bundle harnesses and data buses from different major systems [2]. Unlike aircraft structures, the complexities of systems not only come from the large quantity of connected physical components, but also from the functional interdependencies between systems [3]. Various aircraft systems operate together to achieve one function [4], for example the function of system heat exchange, integrated vehicle system control and avionics information processing all require that several different systems work together to perform their required function. In other words, the whole aircraft will work correctly only if all the associated systems work together to perform to design specification. These overall performance requirements increasingly make modern aircraft become high-level complex products, and thus lead to the further development complexity and difficulty in both product design and manufacturing. Hence, the term complexity in this paper refers to the complexity of aircraft systems only.

The importance of aircraft assembly line design is acknowledged in the literature and recognised as part of the product industrialization [2,5,6]. In this industrialization phase, an assembly process acts as a bridge between design and manufacturing, and integrates installation and test plans with production resources. Therefore, the assembly process planning of modern advanced aircraft has two roles: firstly, integration of design requirements and specifications to satisfy complex product functions; secondly, integration of operations management related activities to support assembly line balancing [7]. The two aspects are interconnected and take place in an iterative working manner through different development phases. Since there is no basis for assembly line balancing and throughput prediction without a competently designed assembly sequence, at the early product development phase the priority task of assembly line design is generating the assembly sequence [8]. Assembly line balancing is then applied to the assembly line plan later in the development process.

Academia has previously suggested that assembly related activities should be taken into account as early as possible in the product design cycle, because it is costly to change the design at the production stage and will make assembly process planning difficult [9,10]. However, in practice, in the aircraft industry design changes often occur in the detailed design and series production phases, which is extremely costly [11]. Government reports reveal that the large numbers of engineering design changes result in low efficiency manufacturing at the final assembly stage for a modern advanced aircraft, even after the aircraft has entered its fifth year of production [12–14]. This is a typical example of development difficulties in the manufacturing stage caused by product complexities, and the design activities of complex systems makes assembly process planning challenging. The literature shows many commercial and military aircraft projects are over cost, over budget and thus do not meet customer requirements [15,16].

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Currently, most assembly process planning is performed based on experience, using 3D CAD assembly models as the main source of product data [17–20]. However, it is difficult to generate the assembly installation and test sequences for complex systems using 3D CAD assembly data alone, because this data does not include the functional interactions between the systems. To ease this situation, the aircraft assembly process planning needs to be more integrated and connected with a wider set of product design data, to allow the aircraft design specifications to be allocated to assembly processes and documentation. A recently developed Systems Engineering (SE) implementation framework, the RFLP (Requirement, Functional, Logical and Physical) can be integrated with CAD and helps manage product complexities by integrating product data from requirements, function and physical design [21,22]. Thus, this research proposes a novel method to help assembly process planners to better understand aircraft system complexities and generate aircraft assembly process plans that take into account both the physical and functional requirements in a complex system using RFLP models.

The paper is structured as follows: Section 2 investigates the relevant literature; section 3 describes the proposed structured approach based on RFLP principles; section 4 shows the implementation of a case study and results. The paper ends with the discussions and conclusions in the last section.

2. Literature review

The aircraft systems integration on an assembly line faces a more challenging environment and working conditions than the systems integration on an iron bird at the design stage. Thus the integration sequence used at the design stage cannot be directly used as the assembly line process. This section investigates the characteristics of aircraft final assembly lines, and the Systems Engineering view of aircraft system development to show how system components are integrated on production aircraft units through installation and test processes. A review of the existing approaches for assembly sequence generation is also provided.

2.1. Characteristics of Aircraft systems integration in assembly line

The product structure of a complex system can normally be represented in a hierarchical manner. If considering the aircraft structure as one of the major systems, the top level hierarchy of most aircraft can be defined as structure, vehicle system, avionic system and mission system [3,23]. In the design and development process, multidisciplinary engineering must be applied to these systems including aerodynamics, materials, mechanical, electrical, information and computer technologies. Aircraft are becoming more integrated with advanced functionalities as a result of rapid developing technologies, which lead to an increase of shared aircraft system functions and interconnectedness design. In aircraft systems design, modern system components are organized in the integrated modular controlled architecture, compared to the old distributed architecture. Generally, the system interdependencies can be concluded as two aspects which are physical and functional interdependence. For a modern advanced aircraft, a brief comparison of the characteristics is shown in table 1.

Table 1. Comparison of system integration characteristics (concluded based on the information from [3,23])

Major system	Physical integration	Functional integration
Structure	Strong	N/A
Vehicle systems	Strong	Medium to strong
Avionic systems	Weak	Strong
Mission systems	Weak	Strong

Physical integration is the most commonly considered characteristic in major systems assembly. Aircraft structural sections, system equipment and components are installed, attached and fixed through physical connections. The functional integration normally refers to the different power sources and information flows between systems. Vehicle systems show both strong physical and functional characteristics due to the functions perform relying heavily on physical connections of other systems or structural components. In a traditional view, aircraft systems are still considered more as functional integration from a point of view at the aircraft level [3,24].

The physical and functional characteristics are interdependent. In the integration process, both physical and functional characteristics have a certain sequence that must be followed. It is easy to see that an aircraft must have airframe parts to assemble structural sections, and these sections and bays then become the basis to support later system components installation. This “structure to system” sequence is the traditional image of aircraft assembly line process, which might be the assembly sequence that most previous research used as the baseline to carry out further work. Some researches use the structure join-up sequence directly as the assembly line process [2,25–27]. Only a few researchers pay attention to the aircraft system work in assembly. However, most of them do not explain clearly the constraints and interrelationships in assembly integration, considering system assembly as a separate and additional working stage [8,28–32]. In an assembly line, the relationship between physical and functional integration is far more complicated than a serial sequence of physical structure followed by functional systems. There are actually certain system pre-equipping works included in the structural assembly stage for technical and operational reasons [33,34]. The “first structure then system” image is mostly based on experience of certain previous aircraft

projects from a very high-level view, which only presents part of the assembly process. Halfmann, Krause and Umlauf show an assembly priority chart of the aircraft interior assembly process from Airbus, which further reveals how physical operations such as structure joining, alignment and system installations are linked to system functional tests [30]. Siedlak et al. highlight the challenges of planning the manual assembly tasks in increasingly complex aircraft electronic systems and propose a scheduling methodology based on discrete event simulation to optimise manual installation of sensors in aerospace production, but do not consider the physical and functional interactions [35].

2.2. Relationship between installation and test in assembly integration

Assembly has a strong link to product functions. As individual parts do not perform functions by themselves, in many cases product function follows the paths of assembly [36]. Aircraft functions, especially system functions, are introduced step by step as the assembly progresses following the assembly plans. Also, unlike structural parts, the aircraft system function “is almost entirely emergent, i.e., not directly related to any property of the implementation” [37]. Understanding the system functions and interactions to generate feasible assembly sequence is the main challenge assembly process engineers face today.

In an assembly line, installation and test are the main methods for physical and functional integration. A typical modern aircraft assembly process 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, assembly line tests are arranged at certain stages in the overall integration process to check and verify the installation quality. The system integration process is therefore an interactive process with installations and tests. Frankenberger states that the “equipment installation of fuselage systems is an enormous workload of high tech manufacturing processes”, and the Airbus A320 fuselage work packages include insulation blanket layout, windows and doors installation, electrical cable wiring, mechanical system lines layout, and different kinds of system tests [29]. As sub-systems and systems are ready to perform their functions through the assembly line process, more tests are arranged at later assembly line stages.

There are different kinds of test involved in the aircraft system design and manufacturing process. Doumbia and Plankl introduce the sequence of system test and integration of airborne systems in Airbus, which consists of the tests in specialized test labs and tests on aircraft in manufacturing and final assembly [38,39]. The tests are performed in the sequence of installed components mechanical and electrical functional tests, sub-system or system function and performance test, and overall system test. Ashford uses aircraft Environmental Control System (ECS) as an example to show the test procedure at Lockheed Martin, covering different levels of interfaces physically present in a modern advanced aircraft: from software coding test, component integration test, vehicle system integration test, air vehicle, ground and checkout test, to the final flight test [40]. Hemmaplardh takes special interest in the test of electrical power system at Boeing final assembly stage. 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 [41]. Compared to the mechanical tests for structural assembly, such as fuselage alignment and fuel tank airtightness test, the system test process is actually the process of testing software applications on aircraft systems. This is because most of the advanced aircraft systems are powered by real-time digital control computers today. Those test activities can be linked with the aircraft system development process in a classical SE ‘V’ model based on Society of Automotive Engineers (SAE) ARP4754A “Guidelines for Development of Civil Aircraft and Systems” as shown in figure 1 [23,42,43].

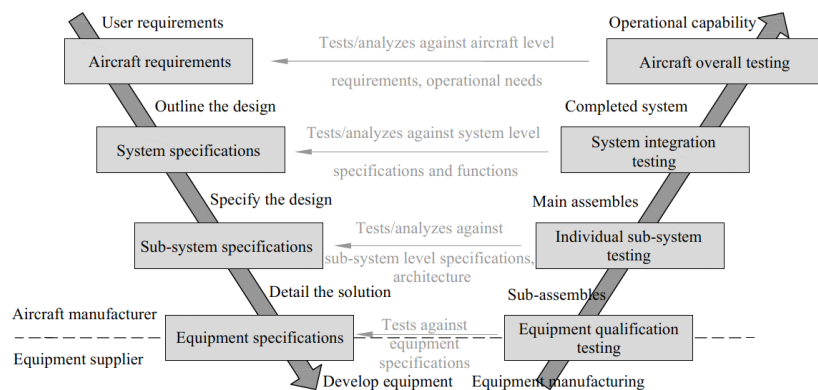


Fig. 1. Aircraft system development overall process ‘V’ model (extracted and combined for system design and manufacturing from ARP4754A [23,42,43])

The ‘V’ model clarifies the “top-down” requirement decomposition and deployment activities, and the “bottom-up” evidence qualification activities towards their left counterparts at each aircraft, system, sub-system and component/equipment level. This design and integration strategy follows the SE verification and validation (V&V) rules, which ensures the requirements traceability. The tests take place in the assembly line and are part of the V&V process. This research is only concerned with production verification tests that take place on the assembly line, and not with design verification tests that are performed as part of the design qualification.

The typical system tests in the “bottom-up” assembly line process include wiring continuity test, power-on/built-in test, and functional test. The main mechanical test for systems is airtightness tests. As the tests are in multiple levels, the system installations are arranged in corresponding sequences to support the tests in different levels. For instance, the cable harness and pipe installations support the continuity tests, and the results of continuity tests support later equipment installations. Similarly, equipment installations support aircraft power-on tests, and further additional installations and functional tests. Recently, the aircraft system design moves to integrated modular controlled architecture means that there is typically more testing required in the assembly process, especially at later assembly stages because many of the system functions are shared in the integrated system architecture. The complete installation of an individual sub-system does not mean that its function can be tested and verified immediately. In the assembly planning, leaving too many tests until all the systems installations are completed will carry significant risk of rework.

2.3. Approaches for assembly sequence generation

The activity of designing an assembly process is called process planning, and the determination of the order of the assembly task is assembly sequence planning (ASP) [44]. These processes consist of certain sequencing or precedence requirements in that certain assembly tasks must precede other tasks [45]. The total assembly work can therefore be broken down into a number of sub-assembly tasks which form logical divisions of the tasks to be completed.

In the literature two types of constraints in ASP of generic product are found which are the absolute constraints and optimization constraints, or strong constraints and weak constraints due to different research studies [44,46,47]. The absolute constraints are the constraints which will lead to infeasible assembly sequence if violated, while the optimization constraints will only cause lower quality of assembly sequences when violated [44,48]. In implementation of ASP, most of previous researchers classified absolute constraints as physical connections constraints and precedence from assembly issues such as manipulability, assembly line layout, and specialized assembly criteria [46,47,49]. In contrast, the optimization constraints include assembly tool, assembly path, and stability constraints [48]. At early conceptual design stage, as much of the information needed for optimization constraints is not available, the absolute constraints are then treated as the primary constraints of ASP.

The concepts of absolute constraints and optimization constraints are introduced to develop algorithms for automatic assembly sequence planning. However, these basic concepts are still based on the manual work of assembly process planning. For complex product, assembly planning work is normally considered as the field of assembly experts [25,50]. In implementation of absolute constraints, the physical connection information is used widely to support assembly sequence generation in ship outfitting and aircraft structure assembly [25,27,51]. The liaison diagram method can be applied for manual and automatic generation of assembly precedence through physical connections [52,53]. Some researchers combine the assembly and disassembly information from the product assembly tree with physical contact constraints to develop sequence generation algorithms. Typical methods include “a tree structure” [54,55], “AND/OR graph” [56], graph-theoretic assembly decomposition method [57], “soft-wired galled networks” [58] and the CAD integrated “assembly tiers” method [59], which both strongly rely on physical contact or joining information. Ghandi and Masehian extend ASP to consider the deformability of flexible parts, supporting a wider range of assembly operations found in ships, aircraft and automobiles, but still they assume a direct physical connection between parts [60]. Since many aircraft pipes, cable harnesses and equipment in a bay do not have direct physical contact, these methods are not appropriate for aircraft systems assembly. It is noticed that other assembly sequencing methods from operations management are not fully suitable for aircraft final assembly line design. This is because the aircraft final assembly process relates more to the product specific features and technological criteria than to manufacturing operation parameters [25], especially at early conceptual design stage of an assembly line.

2.4. SE principles to support assembly integration sequence

Previous research indicates that the aircraft system assembly sequence has many constraints from the functional interactions as well as physical aspect for advanced aircraft system. The problem of system assembly sequence planning can be recognized as the complex system development problem at the manufacturing stage, where SE principles should be used. The practice guidelines in the aircraft sector, for example, SAE ARP4754A states it takes into account the overall aircraft operating environment and functions but does not cover the system integration in manufacturing [43]. Research on SE implementations in manufacturing are mostly about manufacturing management and production system design [16,61,62]. Altfeld emphasizes in his book that “analyses of assembly and integration processes may well change the original layout of the product architecture” [63], which means assembly processes should provide feedback to the design. He introduces the Product & Assembly Tree (PAT) management tool to help sequencing architecture analysis and linking to the integration. In the literature, seldom SE tools are found to support assembly sequence planning directly. However, according to the SE ‘V’ model shown in figure 1, the bottom-up system integration sequence on the right hand side is associated with the top-down requirement decomposition and function allocation processes on the left hand side. In other words, if the detailed requirement decomposition sequence and system function allocations are known, the system integration sequence in the form of a breakdown structure can be generated in a similar way through the requirement traceability links and system verification hierarchy.

Further investigations into aircraft system architecting aspects find requirements are decomposed in a downstream fashion from requirement to functional, logical, and finally the physical domain [64], which is called the RFLP (Requirements engineering, Functional design, Logical design and Physical design) SE framework [65,66]. It expands the “requirements to component” hierarchical approach to more specified development domains, and hence provides a structured bridge better transforming requirements to physical product data and satisfies the integration for a real or virtual product. In the RFLP framework, the functional design deals with the question of what the system does. It defines the aircraft system functions according to the requirement decomposition. The logical design answers what the system is, or what kind of logical components are included in the system. It organizes the logical structure of the aircraft systems in an assembly tree. The final solution is then produced in the physical design. The RFLP approach is mostly used to allow for better data integration and system behaviour simulation during the design process, but in this research it will be used to support assembly sequence planning at an early assembly line design stage.

The information that is required for RFLP modelling is not easily accessible in traditional aircraft engineering data sources and is often stored in a variety of heterogeneous software tools as requirements databases, system schematics, 2D drawings, 3D assembly models and system test documents [7]. Dassault Systèmes has implemented an RFLP modelling approach in the PLM software CATIA V6, which provides an integrated software platform that can be used to implement RFLP model linking product requirements to functional models, logical models and finally 3D assembly models [21,22]. The CATIA RFLP representation allows the creation of structured links between requirements and system functions as well as physical assembly information. These links are created using a manual process based on information from system schematics and product data. This integrated software platform approach removes many of the complexities associated with integrating data from a heterogeneous set of software tools as would be found in most industrial environments. An RFLP solution based on data from a variety of heterogeneous software tools does not yet exist, but recent research into ‘digital threads’ could support such a solution in the future. The aim of the digital thread is to “link disparate systems across the product lifecycle and throughout the supply chain” [67]. It defines a systems integration process that links design, planning, manufacturing and inspection so that discrepancies may be identified and monitored often based on open data principals. Hedberg et al. highlight the need for a “universal plug-and-play solution that would enable native integration of the many systems across the product lifecycle” [68]. They propose the Lifecycle Information Framework and Technology (LIFT) framework that links the disparate software systems used across the product lifecycle to support data driven applications including requirements and physical modelling; however functional and logical modelling are not considered in their framework. Siedlak et al. propose a methodology based on the digital thread to provide an integrated framework for quickly assessing the impact of changes in system design and factory configuration on aircraft performance [69], however their focus is mostly on simulation tools and they do not consider SE.

2.5. Gap summary

In modern advanced aircraft, the systems are complex both in physical and functional integration. Currently, there are no methods that directly support the generation of detailed assembly integration sequences of complex aircraft systems for assembly process planning taking into account both physical and functional integration at the same time. Most previous research considers only the physical connections when defining the initial feasible assembly sequence and ignores the functional interactions. According to the SE ‘V’ model, the integration sequences for advanced aircraft systems should first satisfy the associated functions to meet the decomposed requirements in product hierarchy, and then deploy to associated physical installations. In other words, the aircraft system assembly process should be generated from not only the physical connection information, but also functional information. It is also recognized that the current engineering data sources in supporting assembly planning are not well integrated, which brings risks in the bottom-up integration processes. Systems have shared functions within the integrated architecture connected with different interactions. If this coupled functional information cannot be directly extracted from engineering data source, the verification tests in the assembly line may not have the proper test scope or arranged at the right time. Current industry practice requires manual verification of the physical and functional integration, which is extremely labour intensive and requires expert knowledge of both aircraft systems and assembly planning.

The RFLP framework provides an approach that can model the requirements decomposition process, which finally associates requirements with the 3D physical design data. It has the potential to extract associated functional information to support generating the detailed installation and test sequences. Based on the investigations and gap found, it is proposed to use RFLP models as an integrated engineering data source that can support a new assembly sequence generation approach considering both functional and physical requirements for initial system assembly process planning.

3. Proposed approach

The purpose of this research is to integrate functional and physical design information to support generating an initial feasible assembly sequence in early assembly process planning. It aims to develop a method to plan the sequencing of aircraft systems installation and test at the early assembly line design stage by using a SE framework and integrated CAD to solve the complex system integration problem. In this section, a new approach is presented for initial system assembly process planning. The main elements of the proposed approach are:

- Use SE principles to connect assembly integration activities within the system development ‘V’ model to the overall product development life-cycle thus fulfilling the design and production verification
- Decompose aircraft design requirements to system functions and 3D physical design, and finally allocate to assembly sequences
- Use RFLP modelling to provide traceability from design requirements to assembly activities to help understand how the assembly integration satisfies the requirements
- Generate initial feasible system installation and test sequences following RFLP modelling rules defined in the method

3.1. SE view of assembly activities in the aircraft system development model

The functional interdependencies of system components contribute much to the development difficulty of the overall system integration process in both design and manufacturing. In assembly line conceptual design stage, the assembly process planning should consider both physical and functional constraints to generate a feasible process. This is because the installation and test activities in an assembly line must guarantee a fully functional aircraft with no need for rework. In this research an extended version of the SE ‘V’ model is used to describe the integration between the aircraft system design process and the assembly line design process. To deal with the complex systems integration problems and develop an integrated approach to assembly process sequence generation, it is important to understand the relationship between early product design and assembly line design in their life-cycle models, as well as their relationship to system integration at the assembly line. As shown in figure 2, a modified ‘V’ model is proposed in this research to clarify the engineering outputs of each design stage in the top-down process, and connect the system tests to assembly line test activities and supported installations in the bottom-up process. In current industrial practice, most of the assembly line design takes place concurrently with aircraft product design [2]. Assembly process planning is the most important part of assembly line design. The early assembly process planning top-down workflow is therefore added in the same ‘V’ model as the aircraft design, to help understand the needs of engineering data outputs that support assembly sequence generation. It should be noticed that some activities with dashed line are actually not part of the assembly line activities. These supplier and flight test activities are kept in the model for the purpose of showing a full development processes.

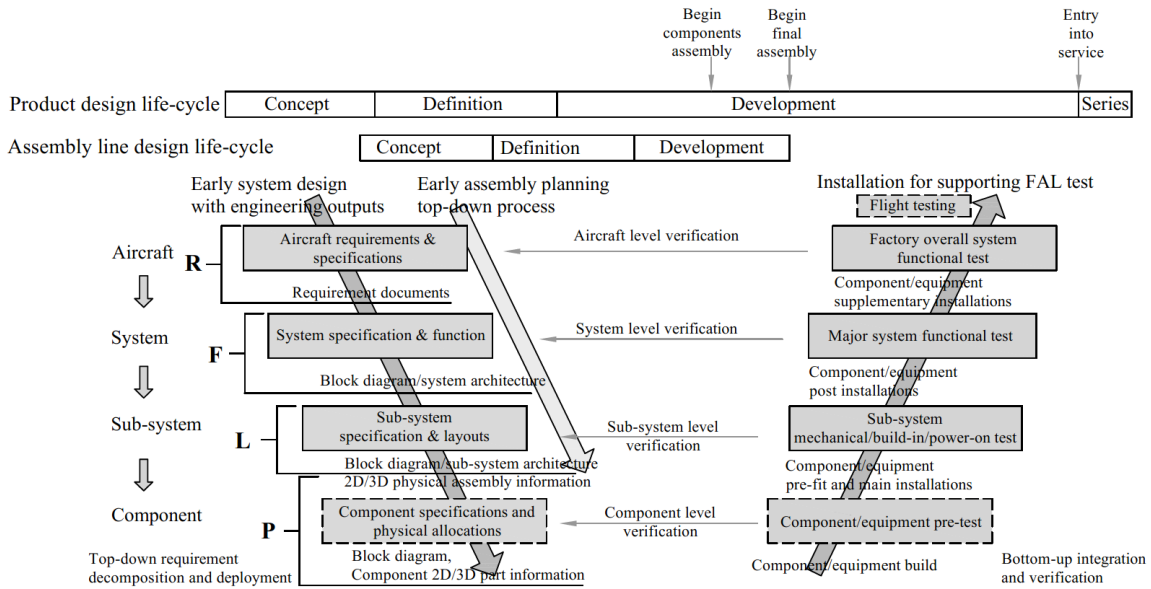


Fig. 2. Aircraft system integration ‘V’ model from assembly line view (concurrent life-cycle model based on [2])

In figure 2, the left top-down process represents the requirement decomposition and deployment activities with the engineering outputs produced at each level of the ‘V’ model hierarchy. It should be pointed out that the architecture of the engineering outputs at the system and sub-system level is not exactly the same. The architecture output at system level is mostly organised as function tree, whereas at sub-system level, the architecture outputs may refer not only to a more detailed function tree, but also to a logical product structure tree or assembly tree of system logical components. The bottom-up process in this figure can be considered as the assembly integration sequence driven by structured tests. Tests here act as “stage gates” to allow further installations and tests. In other words, the top-down assembly line design process is constrained by these tests from the right side. Then the detailed integration sequence which is in the form of breakdown structure can therefore be generated through these functional tests and their installations. The engineering outputs from the left side activities, such as system schematics in the form of block diagram, product 2D drawings and 3D models are supposed to support the right bottom-up side assembly line activities to generate assembly processes. However, it is believed that in current industrial practice such functional and physical

engineering information are not well integrated in the design stage. Once the separate functional and physical information are released to support assembly process planning, they need to be linked manually by the assembly process engineers based on their own knowledge and experience first. Although some guidelines and criteria are also released in the design process to help assembly process planning, the assembly sequence planning result still depends too much on experience to make the precedence decisions from the poor integrated product information [7]. The needs of the developed approach are further specified as:

- (1). Use SE principles and framework to decompose and deploy requirements to the final product design data, and embed requirement traceability information within
- (2). Use integrated CAD to link system functional and physical information to produce the engineering data source that support assembly planning
- (3). Adapt aircraft system function to assembly line environment and then generate the initial feasible test and installation breakdown structure

3.2. Assembly sequence generation method

The proposed method in this paper provides a structured approach to generating an initial feasible assembly sequence and uses the SE RFLP framework to provide an integrated design data source for assembly process planning. Building on the RFLP modelling approach, the assembly integration sequence generation method is shown in figure 3.

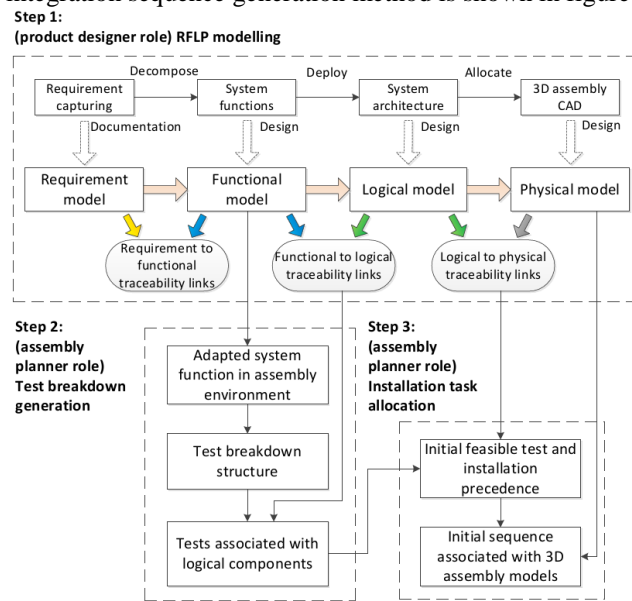


Fig. 3. Structured assembly integration sequence generation using RFLP model

The method has three steps. The first step is finished by the aircraft system designers to produce the RFLP models and embed traceability links between the RFLP models. This step builds on the standard RFLP modelling process and it is assumed that in an industrial implementation, this step would be completed as part of the product life-cycle management (PLM) data in the aircraft design process. This is the step of preparing engineering data source through the requirement decomposition process. The RFLP modelling follows basic SE principles for system function and interaction design. Specialized modelling rules have been developed to enhance the RFLP models, and ensure that they support the functional design process and are suitable for assembly planning reuse. These modelling rules are part of the novelty in the proposed method. Step 2 and step 3 are the roles of assembly planner and are another aspect of the novelty. First in step 2, the assembly planner reuses the functional model to identify functional dependencies towards the assembly environment for production test breakdown generation. Then, the test breakdown is deployed to associate with logical components through the information from the logical model. In step 3, this breakdown structure can be further deployed to link with 3D physical CAD models thus produce the initial feasible integration sequence. The method has been implemented in Dassault Systèmes CATIA V6 SE package, and the RFLP model data are managed in Dassault Systèmes ENOVIA V6 which is the PLM software for CATIA V6. This approach has been selected to simplify the implementation, removing the complexities associated with integrating a heterogeneous set of software solutions as would typically be found in industry.

In the implementation, the RFLP modelling data is used as the engineering data source to support assembly process planning. In the RFLP model, each view of RFLP has a respective model and there are embedded links between the requirements, functional, logical and physical models to ensure the requirement traceability, which associates RFLP models with their implementations. For example, a single requirement “system shall feed fuel to engine” may be associated with several functions, i.e., “provide fuel feed pressure”, “feed tank fuel to engine” and “transfer fuel” in the functional model. These functions can be

further decomposed to a logical breakdown structure including “feed pump”, “feed switch-off valve”, “cross-feed valve”, “feed pipe”, etc. These logical components are finally designed in 3D physical models. In the RFLP framework, detailed implementations can use the information provided in these associated models, like system behaviour modelling and engineering BOM (Bill of Materials). The assembly integration sequence can be treated as a breakdown structure constrained by tests. The implementation of assembly integration sequence generation proposed in this paper follows this principle and picks up information directly from the different RFLP models for the integration deployments. The functional architecture and interactions in the functional model support generating the functional test precedence of the test breakdown structure. The test breakdown can be further deployed to required logical components and the final physical components through logical and physical model respectively.

Integrated CAD is used in this approach to connect different domains of RFLP model, and support extracting information for assembly sequence generation. In concurrent engineering, the advantage of using integrated CAD here is that it has better covering and integrating of the design and assembly information at different life-cycle phases, especially at their early development phases. Early in the design process much of the information needed by assembly planning is not available. As the design progresses and parts of the system design are frozen, the level of information uncertainty in the design decreases, thus more information can be extracted from the product model [36]. From the SE view, the proposed approach should be applied in an iterative way to give greater benefits. In this approach, the integrated CAD also connects two user roles: the aircraft system designer and assembly planner. It helps people better understand the product characteristics and manufacturing constraints through direct linked and associated information, and mitigates risks at the source of the problem rather than using experienced based approach.

3.3. RFLP modelling (step 1)

RFLP modelling rules have been developed to ensure the RFLP models follow the basic SE principles in aircraft system function design, and support the model reuse for generation of assembly integration sequence. These rules are all used in method step 1. In this research, there are three modelling rules: the boundary identification rule, interaction definition rule and traceability definition rule. The modelling rules use the basic SE concepts based on the book from Kossiakoff to define the generic system function and interactions [70]. The functions catalogue is defined as input, transformative and output function, while the interactions between functions are defined as signal, data, energy and material. The modelling rules in this research follow these basic principles and adapt them with CATIA V6 RFLP implementations.

3.3.1. Boundary identification rule

As aircraft systems are the typical example of system of systems, to better understand the interdependencies, it is important to identify the system boundary and case study scope in modelling. The boundary identification rule is created to identify the core functions of interest as follows:

- (1). System functions are subdivided as internal system functions and external system functions.
- (2). Internal system functions are the functions within the research scope of the case study. They are the main functions that satisfy the system design requirement. For example, if it is a wing section case study, then the system functions within the wing section are identified as internal system functions.
- (3). External system functions are the functions outside the case study scope, but they may have influence on the internal system functions. These functions can also be the functions providing system working conditions and operational environment. Using the wing section for example, the external system functions can be the system functions in the fuselage section, like manage electrical load and generate conditioned air.
- (4). Top level of system functions can be created by aircraft structural zones or sections separately depending on the case study scope.

3.3.2. Interaction definition rule

The interaction definition rule defines the types of interactions that can be created between the RFLP models. Due to the limitations of interaction types can be defined in CATIA V6, the system interactions in functional and logical model are classified into two categories: control and data. The interaction definition rule is mapped with the catalogue of Kossiakoff [70] and presented in table 2.

Table 2. Interaction definition rules mapping with generic classification

Interactions from Kossiakoff	Interactions in CATIA V6	Interaction definition
Information (Signals)	Functional dependency (Control)	Electrical flow: system control signal
Information (Data)	Functional dependency (Data)	Electrical flow: system data
Energy	Functional dependency (Data)	Electrical flow: electrical power Mechanical flow: fuel, hydraulic, cooling air, pneumatics, water
Materials	Physical dependency	Physical connections in 3D CAD model

3.3.3. Traceability definition rule

The traceability definition rule defines the rules that must be followed when connecting items in the RFLP models. The traceability definition in CATIA V6 allows links to be created between any items of the RFLP model, but in order to better manage the tracing information and simplify the modelling, in this research the traceability definition rule is developed to manage the link modelling between RFLP models as shown in table 3. An example of the rules is illustrated in figure 4. There are both “one to one”, “one to many”, “many to one”, and “many to many” relations in the traceability modelling.

Table 3. Traceability definition rule

Rule	Details
Modelling sequence rule	Links should be created between every two models following the R-F, F-L, and L-P sequence. No jump links are allowed.
Root link first rule	Links should be created between the root nodes of top level models first
Bottom priority rule	Links are created in priority at the bottom level of RFLP models

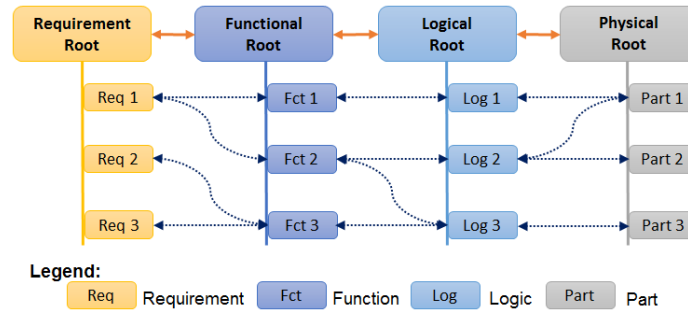


Fig. 4. Simplified example of the traceability definition rule

3.4. Test breakdown generation (step 2)

Once the RFLP models have been created in step 1 of the process, the functional information including the hierarchy of system function, dependency between internal functions and external functions, and interactions between the sub-functions are all defined. Each sub-function has a category property, which can be used to identify whether it is an input, transformative or output function. As introduced previously in the literature review, aircraft system functions follow the path of assembly in integration. In the method step 2, the initial feasible test breakdown structure for system functions can be generated as the following sub-steps:

- 2-1. Start with the ‘function’ hierarchy in the functional model as the baseline. Identify all unavailable interaction links between the sub-functions in the baseline model, including internal function and external function model according to manufacturing technical, operational, environmental and safety constraints.
- 2-2. Introduce test solutions for aircraft systems assembly line test, for example: ground power, air, hydraulic, specialized test facilities, etc. Then examine these unavailable interactions links again to find whether they are still unavailable under the conditions provided by the test solutions. These test solutions may come from the system verification requirement or customer requirement.
- 2-3. Remove the unavailable interaction links from the baseline and update the adapted interactions from test solutions.
- 2-4. Create a new ‘test’ hierarchy adapted from the ‘function’ hierarchy created in step 2-3. The ‘test’ hierarchy is created by determining a test task for each sub-function of the internal functions in the functional model. External functions are kept unless they are replaced by the functions of test facilities in the assembly line.
- 2-5. If there are test tasks in parallel, interaction links in two directions, or test task links multiple test tasks, identify which test associated sub-function will emerge first in system integration process. Sort the hierarchy to remove the interaction links used at later stage and have a one way sequence test breakdown structure.
- 2-6. Associate the test breakdown structure with logical components through the embedded function to logical traceability links in the RFLP models.

The simplified wing section fuel system example mentioned in section 3.2 will be used to explain briefly the sub-steps in step 2. There are two input functions “store fuel”, “provide engine feed pressure”, one transformative function “feed tank fuel to engine”, and one output function “transfer fuel”. They are all internal functions which are defined in the functional model, and have simple interactions and a function hierarchy as follows:

- Mechanical interaction flow: “store fuel”, “provide engine feed pressure”, “feed tank fuel to engine”, “transfer fuel” are arranged in a one-by-one serial sequence

- Power interaction flow: electrical power from the external function “distribute electrical power” in other aircraft structural sections is linked to “provide engine feed pressure” and “feed tank fuel to engine” in the wing section.
- Function hierarchy: internal functions are arranged in series from “store fuel” to “provide engine feed pressure”, “feed tank fuel to engine” and “transfer fuel”.

The availability of these interactions is then examined by wing assembly line constraints. Normally, the fuel tanks cannot be tested by filling them with fuel, because fuel is not allowed in an aircraft assembly line for safety reasons. Other constraints include no extended dry running of fuel pumps in empty tank is allowed, and the electrical power provided from other structural sections is not available. Thus, none of the mechanical and power interactions from system design are available. However, to verify the installed system components, industry could use test solutions to rebuild these interactions by using pressurized air to replace the fuel in the tank and fuel system, and introducing specialized ground facility to provide external electrical power. It is also the common production test strategy to use static system testing to replace the system dynamic performance testing, which means airtightness tests are used for fuel system test, and feed pump voltage test is used for pump running test in an assembly line. Therefore, the adapted function hierarchy is then generated by keeping most of the design interactions but changing fuel interaction to air interaction flow. According to the embedded function to logical traceability links between functional and logical models, the system logical components information for each sub-function can be accessed directly in the RFLP models. A test breakdown structure can be produced to arrange test tasks for these sub-functions in the adapted hierarchy respectively, and further associated to logical components needed. In this example, the test sequence result of step 2 is: “fuel tank airtightness test”, “feed pump input voltage test”, “engine feed power-on test” and “fuel system airtightness test with tank”.

If adding a new input function “provide APU feed pressure”, and another transformative function “Apply APU feed”, the system test breakdown is then changed to a tree structure where the associated two transformative sub-functions and two input sub-functions are all in parallel. Additional checks then taken place for these parallel test tasks to find the priority task from design and manufacturing factor. Although at early assembly planning stage, an initial feasible sequence may have many parallel tasks, the assembly planner could review the sequence and make improved decision when additional technical and operational information are available in later stages, such as more system control constraints are found from other aircraft sub-systems in the later design, or later accessibility analysis result indicates that certain system components are required first.

3.5. Installation task allocation (step 3)

In step 3, the test breakdown structure is further deployed to a detailed installation and test tasks sequence by reusing the traceability links between logical and physical models. The logical components are now linked to 3D CAD models in the initial feasible sequence. The functions of assembly line facilities are clarified and linked with the ‘test’ hierarchy in step 2. In the generated sequence, the required installations are all treated as the Finish-No-Later-Than (FNLT) tasks for the tests. This is because if the physical installations are arranged after the generated test stages, the system functions cannot be verified properly. As a result of that, the overall process will be delayed to wait for the system installations, or it may cause potential risks in later system operations, such as the risk of system damage by incorrect power distribution or system out of control. An additional benefit is that these facility functions can be expanded to ground facilities and test equipment needed in the overall assembly process. This helps in understanding at which stage the ground facilities and equipment are required. For the fuel system example, the initial generated sequence can be presented in table 4 in a bottom-up tree structure.

Table 4. Initial feasible integration sequence of the fuel system example (with simplified physical component names for demonstration purposes)

Stage 4		
Test task	Fuel system airtightness test with tank	
Required installation	All the fuel system installations (3D CAD models)	
Stage 3		
Test task	Engine feed power-on test	APU feed power-on test
Required installation	Feed valve 1, Feed valve 2, Feed valve 3, Feed valve 4	APU feed valve 1, APU feed valve 2
Stage 2		
Test task	Feed pump input voltage test	APU feed pump input voltage test
Required installation	Feed pump 1, Feed pump 2, Feed pump 3	APU feed pump
Stage 1		
Test task	Fuel tank airtightness test	
Required installation	Wing section fuel tank	

A detailed case study to illustrate the proposed method is presented in the following section.

4. Case study

The case study is developed based on the Cranfield University student group design project aircraft E-15, which is a preliminary design of a more electric business jet equipped with next generation of avionics [71]. The aircraft project data include information from initial requirements to system schematics and original 3D assembly layout models. Three major aircraft systems in the nose bay section of E-15 aircraft and the relevant requirement documentations are selected for the case study. This case study uses the 3D CAD models of the structural components from the design data as basis and develops the new systems physical models in the RFLP modelling environment. The case study is composed of 16 requirements, 18 functions, 20 logical items and 23 physical components.

4.1. Step 1 implementation: RFLP modelling

Following the method presented in Section 3, the first step (step 1 shown in figure 3), the aircraft requirements entered in the ENOVIA V6 system first, and then imported into CATIA V6 RFLP module for later functional and logical design (see figure 5).

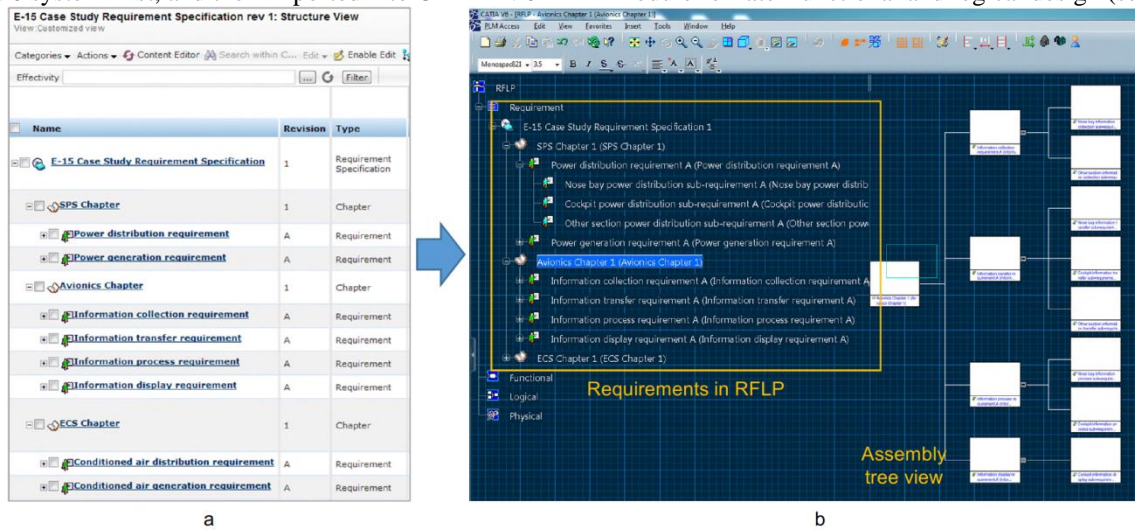


Fig. 5. (a) Requirements in ENOVIA V6 PLM system; (b) Requirements in CATIA V6 RFLP module

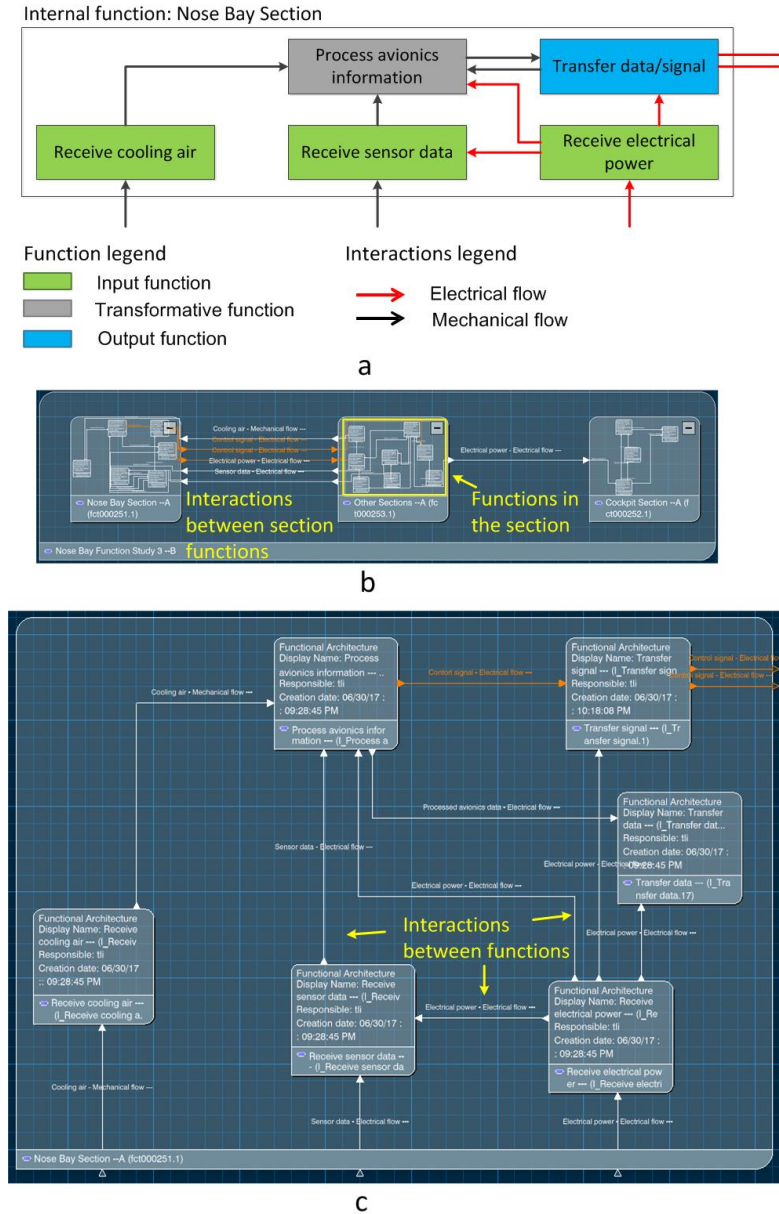
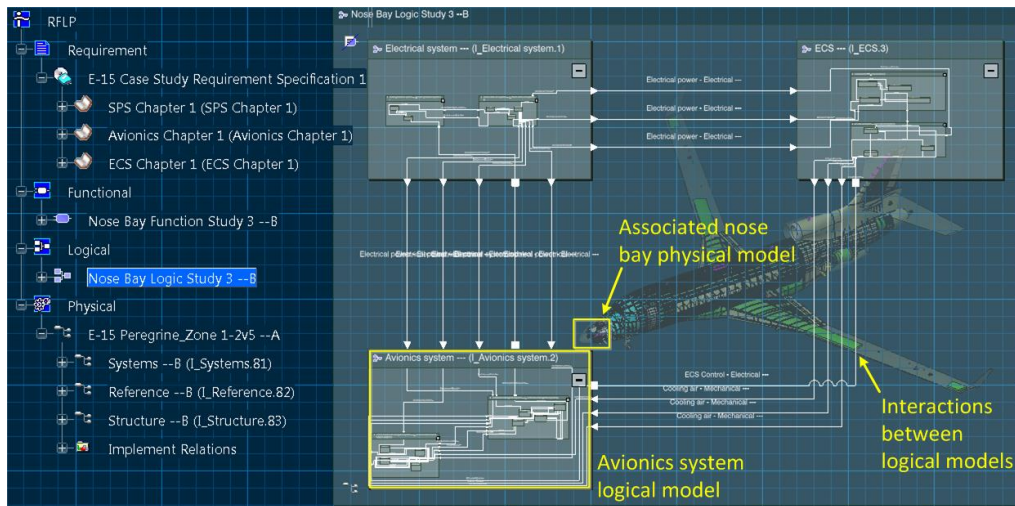


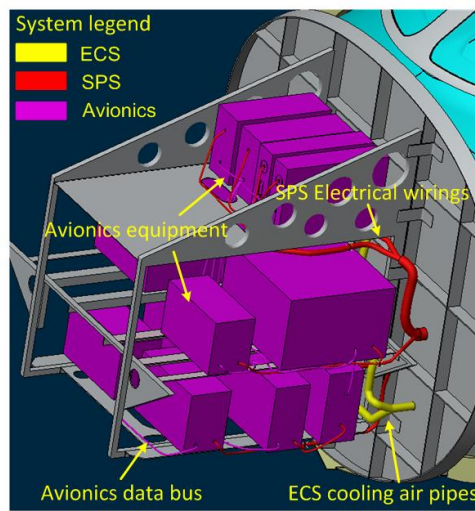
Fig. 6. (a) Extracted from nose bay section as internal function in 2D block diagram; (b) Internal and external functional models in CATIA V6; (c) Nose bay section functional model and interactions

Following the boundary identification rule, the case study functions are subdivided into one internal function, the nose bay section, and two external functions which are the cockpit section and other aircraft sections. Figure 6 (a) shows part of the system functions design as a 2D block diagram. The functions which relate the processes of sensing and inputting signals, data and energy into the system are defined as input functions, such as “receive sensor data” and “receive electrical power”. The “transfer data/signal” function transfers system signals and data out of the system, thus is recognized as the output function. The “process avionics information” is defined as transformative function as it links to the input and output functions. System interactions between functions are first defined in the 2D block diagram, then detailed in CATIA V6 following the interaction definition rules. Figure 6 (b) shows the functional modelling results with functions of three top-level sections and interactions between them. Figure 6 (c) is a sub-function view of the nose bay section function.

The system logical model describes the composition of the three aircraft major systems in terms of logical system, sub-system and components. The interactions from the functional model are further specified and allocated to individual system logical components following the same interaction modelling rule. Finally, the 3D models of nose bay system components are created as physical CAD models in CATIA V6 assembly module. The RFLP models are now integrated in the same software viewpoint. Figure 7 (a) shows all the RFLP models with the activated logical modelling view and physical assembly model at background. The 3D physical model in figure 7 (b) includes avionics equipment, avionics data bus wirings that transferring data and signals between equipment, ECS pipes that cool the avionics computing equipment, and the SPS wirings that provide electrical power for nose bay equipment.



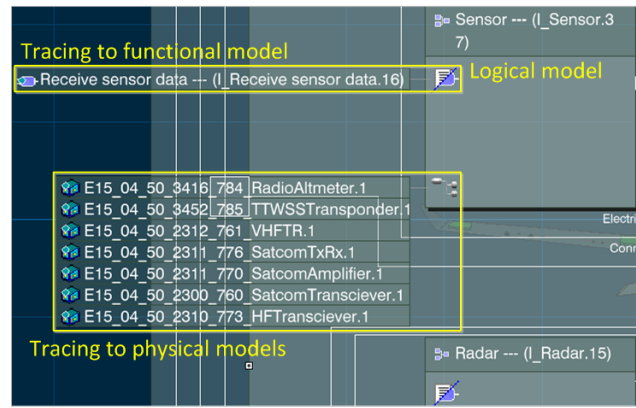
a



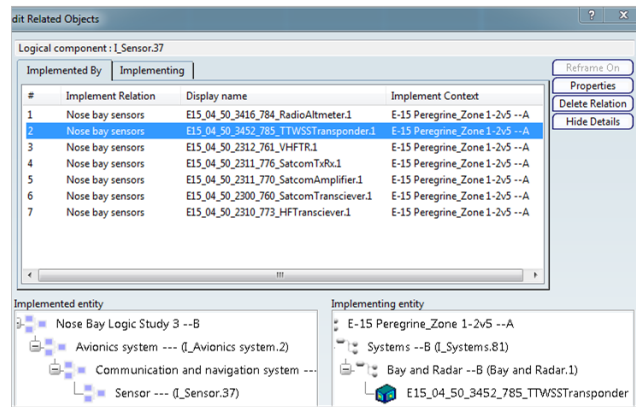
b

Fig. 7. (a) RFLP models with activated logical view; (b) 3D physical system assembly models of nose bay section

The traceability links are embedded in the models using the traceability definition rule through the overall modelling process. Figure 8 shows the logical component “sensor” linking with function “receive sensor data” and several 3D assembly CAD models. The traceability information can be accessed directly through the linking icons on individual item in the models, or generated as traceability matrices for every two RFLP models. The SE RFLP model of the nose bay section is now complete, and this is the end of step 1 in the method.



a



b

Fig. 8. (a) Example of traceability links; (b) Detailed traceability information

4.2. Step 2 implementation: test breakdown generation

Step 2 of the process generates the hierarchical test breakdown from the RFLP model. As mentioned in figure 2, some aircraft systems cannot be fully tested in the assembly line, such as the fuel system, avionics system, and the functions requiring engine running and aircraft inflight. The method in step 2 examines the working conditions of aircraft system functions in the assembly line to identify the availability of system interactions for the assembly integration test. This helps to get an assembly view of system functions and to transfer the system functional hierarchy into test requirements and sequences in the form of test breakdown structure. The generic assembly line constraints used in this case study are listed in table 5 with influence on assembly integration and test solutions.

Table 5. System constraints in the assembly line and solutions

No.	System integration constraints	Influence	Test solution
1	No power plant running	Electrical power from other sections not available	Use ground electrical power
2	No ram air and aircraft generated ECS cooling air	ECS cooling air from other aircraft sections not available	Use ground cooling air instead
3	No dynamic inflight data (speed, altitude, acceleration)	Inflight information for avionics not available	Use simulated data from test equipment
4	No fuel in the fuel tank	Fuel quantity data not available for avionics	Use simulated fuel quantity from test equipment

The nose bay section functions in figure 6 (a) are then adapted to the integration tests with those constraints by switching system functions to verification test tasks and adding assembly line facilities as shown in figure 9 (a). There are two way interactions between “avionics functional built-in self-test” and “avionic overall functional test”. To have a one way sequence, their associated functions are examined in step 2-5, and find the output interaction of “avionics functional built-in self-test” should be kept. Similarly, the test task “electrical wiring continuity test” has multiple links to later tests, but the “Net switch” in the avionics data transfer test is required first. Thus, the interactions links between other two tests are removed. Thus, the test stages are decided and the adapted test block diagram is resorted and deployed to logical components through the functional and logical traceability links in figure 9 (b).

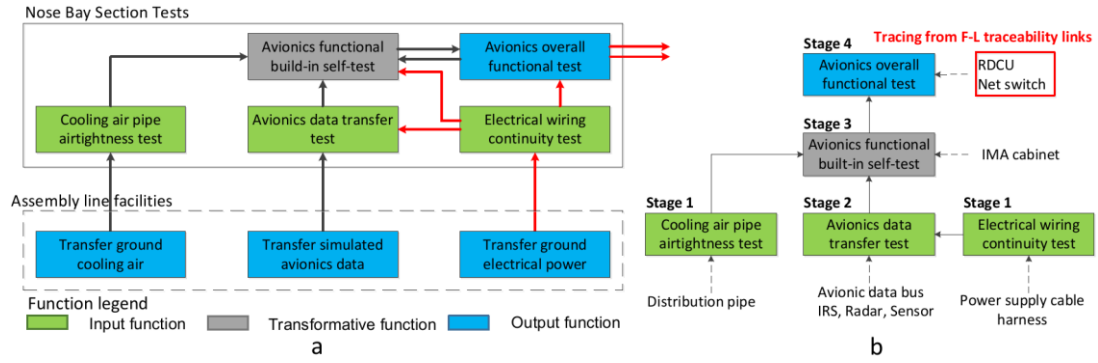


Fig. 9. (a) Adapted test block diagram based on figure 6 (a); (b) Test breakdown with logical components

4.3. Step 3 implementation: installation task allocation

Following the method in step 3, the installation task allocations are finally finished by further deploying the logical components to detailed 3D physical models through the embedded logical to physical traceability links. Each logical component is linked with at least one 3D model. For instance, the logical component “radar” is linked to “weather radar” and “TTWSS radar” in this case study. The final generated initial feasible assembly sequence is shown in figure 10 and represented in the 3D assembly view. The assembly steps are shown starting from the bottom of the figure and building upwards to the top. The physical installations for each stage test are shown in the FNLT task sequence. In figure 10 (b), the numbering of the physical items shown in figure 8 is removed for a clearer view of the result.

The results show that for this case study the cooling pipes should be installed first in stage 1, and then tested for airtightness. At the same stage, the electrical wiring should be installed and tested for continuity. Since there are not enough additional constraints at this stage to produce more detailed sub-sequences, the piping and electrical work can be arranged in parallel for the initial feasible sequence. In stage 2, the avionics data bus and equipment in the lower rack should be installed to support the avionics data transfer test. Then at stage 3, the “IMA cabinet (IMA1)” is installed in the nose bay and together with the systems previously installed to have the built-in self-test. Finally, all the system components and equipment from three major systems are installed, and the avionics overall functional test can be performed. The resulting assembly sequence makes use of ground equipment and assembly line facilities to allow early testing of each installation at each stage in the integration design process, to minimise the risk of identifying errors late in the assembly process.

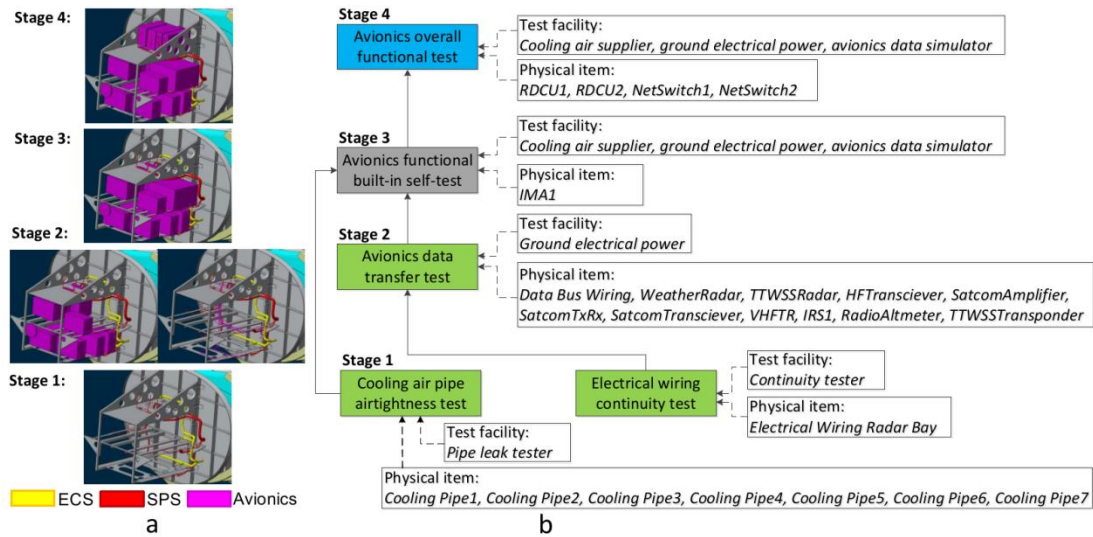


Fig. 10. (a) Integration sequence in 3D assembly view; (b) Detailed physical installation components with associated test tasks and facilities

Figure 11 shows part of the extracted requirement traceability results from the RFLP models that link to test tasks. They are sorted into several levels: requirement, design function, assembly line tests, logical components and 3D physical models. It should be pointed out that the traceability works in two ways which allows understanding of both the requirements decomposition and the integration processes from components to finished nose bay systems. Besides, as the functions are adapted into tests in figure 9 (a), at assembly line design stage it is easy to know which tests and associated system components are used to satisfy the requirements through the traceability links in RFLP models. The output of the process is a feasible assembly sequence to support the test hierarchy thus better guarantee the system functions and requirements. By following the

method presented in this paper, the functional requirements for testing are considered in the assembly sequence, and not just the physical connections between the parts. The resulting assembly integration sequence therefore leads to a manufacturing process that is robust due to the integrated testing at each stage and with reduced need for expert knowledge of the interactions between different aircraft systems.

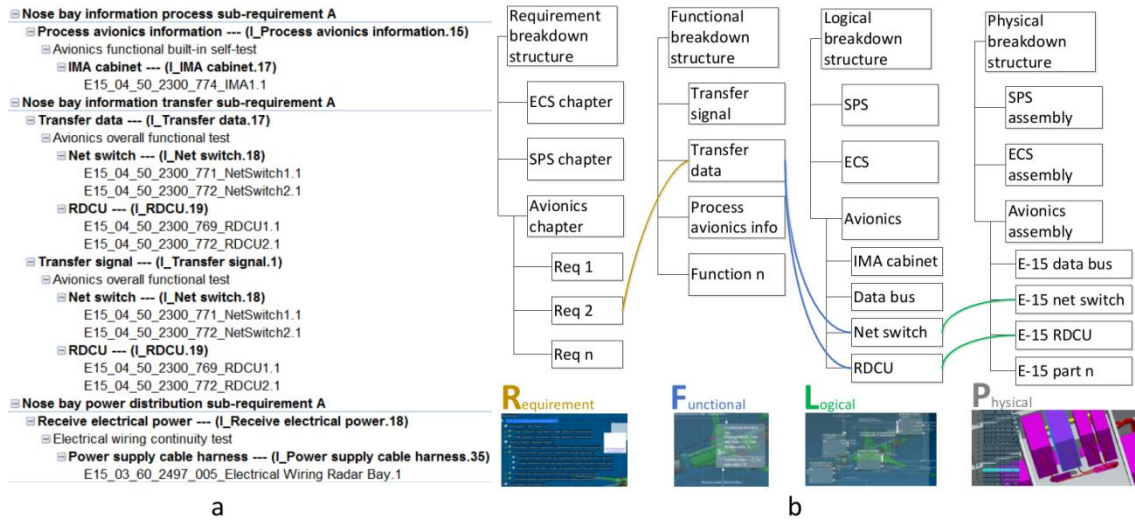


Fig. 11. (a) Part of extracted requirement traceability links with test tasks; (b) Simplified illustration of case study requirement traceability

For comparison, it is useful to consider how other conventional ASP methods could be applied in this case study. If using the liaison diagram method as an example [52], the number of feasible sequences would be vast. This is because there are many physical components, especially the equipment in the nose bay, that have relatively few physical precedence relations at the early development stage in the design process. As the equipment only has a general layout at this stage and many components do not have direct physical connections between each other, the equipment assembly process can be arranged in almost any order by using the conventional ASP methods. Furthermore, the generated sequences would not take into account the functional behaviour of the system, but only the physical interactions. Hence, the method presented in this paper provides a repeatable process for initial feasible assembly sequence planning for complex systems that cannot be done using existing ASP methods.

5. Conclusions and future work

This research investigates the issues of complex systems integration in aircraft assembly and provides a novel method to generate the initial feasible installation and test sequence at an early stage, without the need for extensive professional experience and knowledge of both aircraft systems and assembly planning. The main novelty in this research is the development of a structured approach for early stage assembly process planning that combines both physical and functional integration. By applying SE principles and using RFLP modelling it also provides an opportunity for both design and manufacturing to understand each other better through the traceable information from requirement to functional, logical and physical multidisciplinary views. The proposed method changes the product development workflow from “requirement-part-assembly” to “RFLP-assembly”, and uses SE principles for aircraft assembly integration, which ensures the generated sequence better connects to design requirements, avoiding the risks in manufacturing decision making. The generated results are thus much more reliable than the traditional experience-based approach. The method uses integrated SE to ensure that system production verification requirements are considered in the system design and process planning. By applying this method, the overall product development would benefit from improved design quality, rapid response for design complexities and more reasonable manufacturing decision making.

The proposed approach in this paper is tested on a case study with simplified design data in the nose bay section of an aircraft. The results show that the approach can produce a feasible assembly integration sequence, and the traceability links in the models allow the assembly planner to gain a much better understanding of the design dependencies and how they affect assembly and test planning. The case study indicates that installation and test precedence can be generated from the functional dependencies of aircraft complex systems if such information is integrated into 3D CAD and PLM models as the engineering data source. The case study considers different aircraft systems and modelling the interactions to give a multidisciplinary solution rather than looking at one system or structural sections only. The case study result has the advantage that the sequence follows the integration path of aircraft system functions rather than only generating from 3D CAD physical connection information. Thus it avoids potential system re-installations and re-tests caused by system functional issues at later flight test stage. It is suggested that a large case study with more detailed design data including more structural sections be developed to further test the approach.

Future work would be required to develop the demonstrator tool towards an industrial solution. Firstly, the creation of links in the RFLP model was found to be extremely time consuming and it is proposed that in order to achieve a more scalable solution, the modelling efficiency should be improved by creating templates to allow fast picking of pre-defined interactions rather than inputting all the different interaction information manually. Secondly, the method has been implemented using an integrated software platform CATIA v6, which has removed many of the data integration challenges that would be found in a complex industrial environment based on a heterogeneous set of software tools. It is proposed that recent research into digital threads could be used as the basis for a more flexible solution that could create and maintain complex data linkages between different software tools. Finally, although the aircraft structure is out the scope of this research, if considering aircraft structural assembly as part of the overall aircraft function realization process, structural sections are also a major system of an aircraft from the SE view. In this way, the proposed approach can be applied to more complicated situations when some system installations are involved in the structural section assembly, such as the equipment pre-equipping in the wing section. Although the method has been developed for complex aircraft systems integration it could also be applied to a range of complex engineering systems including ship outfitting and the nuclear industry.

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