CRANFIELD UNIVERSITY

TAO LI

AIRCRAFT ASSEMBLY PROCESS DESIGN FOR COMPLEX SYSTEMS INSTALLATION AND TEST INTEGRATION

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
Aerospace Engineering

PhD
Academic Year: 2015 - 2018

Supervisor: Dr Helen Lockett
Associate Supervisor: Dr Craig Lawson
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ABSTRACT

The assembly line planning process 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. From a systems engineering view point, this activity is part of the complex systems integration and verification process. At the early conceptual design phase of assembly line planning, the priority task of assembly process planning is to understand product complexities in terms of systems interactions, and generate the installation and test sequence to satisfy the designed system function and meet design requirements. This research proposes to define these interactions by using systems engineering concept based on traceable RFLP (Requirement, Functional, Logical and Physical) models and generate the assembly integration sequence through a structured approach. A new method based on systems engineering RFLP framework is proposed to generate aircraft installation and test sequence of complex systems. The proposed method integrates aircraft system functional and physical information in RFLP models and considers these associated models as new engineering data sources at the aircraft early development stage. RFLP modelling rules are created to allow requirements, functional, logical and physical modes be reused in assembly sequence planning. Two case studies are created to examine the method. Semi-structured interviews are used for research validation. The results show that the proposed method can produce a feasible assembly integration sequence with requirements traceability, which ensures consistency between design requirements and assembly sequences.

Keywords:

Assembly line design; assembly process planning; complex systems integration; RFLP modelling; requirement traceability

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LIST OF ABBREVIATIONS

A/C	Aircraft
ALB	Assembly Line Balancing
ASP	Assembly Sequence Planning
AVD	Aircraft Vehicle Design
BOM	Bill of Materials
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacture
CATIA	Computer-Aided Three Dimensional Interactive Application
CG	Centre of Gravity
CNI	Communications, Navigation and Identification
DFA	Design for Assembly
DFMA	Design for Manufacture and Assembly
DSM	Design Structure Matrix
EASA	European Union Aviation Safety Agency
ECS	Environment Control System
EWIS	Electrical Wire Interconnect System
FAA	Federal Aviation Administration
FAL	Final Assembly Line
FCS	Flight Control System
FEA	Finite Element Analysis
FFT	Factory Functional Test
FMEA	Failure Modes and Effects Analysis
FMES	Failure Modes and Effects
FNLT	Finish-No-Later-Than
FTA	Fault Tree Analysis
HoQ	House of Quality
IMA	Integrated Modular Avionics
JIT	Just in Time
LRU	Line Replaceable Unit
MBD	Model Based Design
MBOM	Manufacturing Bill of Material

MBSE	Model Based Systems Engineering
MoM	Matrix of Matrices
NACA	National Advisory Committee for Aeronautics
PAT	Product & Assembly Tree
PBS	Product Breakdown Structure
PLM	Product Life-cycle Management
PMI	Product and Manufacturing Information
PPR	Product, Process, Resource
PSSA	Preliminary System Safety Assessment
QFD	Quality Function Deployment
RDCU	Remote Data Concentrator Unit
RE	Requirement Engineering
RFLP	Requirements engineering, Functional design, Logical design, Physical design
SAE	Society of Automotive Engineers
SaaS	Software as a Service
SE	Systems Engineering
SPS	Secondary Power System
SysML	Systems Modelling Language
TTWSS	Traffic Terrain and Weather Surveillance System
UML	Unified Modelling Language
V&V	Verification & Validation
VIU	Vehicle Interface Unit
VMS	Vehicle Management System
ZSA	Zonal Safety Analysis

1 INTRODUCTION

1.1 Background and motivation

1.1.1 Complexity of modern aircraft systems

The system components integrated in modern large scale aircraft are a typical example of complex systems (Thomas et al., 2015), and normally include a large number of equipment, pipes, wire bundle harnesses and data buses from different major systems (Mas et al., 2013). Modern aircraft system design covers multidisciplinary topics from mechanical, electrical, pneumatic, hydraulic and thermal fields to digital computing. 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 (Seabridge, 2010a). Various aircraft systems operate together to achieve one function, such as the heat exchange, integrated vehicle system control and avionics information processing (Moir and Seabridge, 2008). In other words, the whole aircraft will work correctly only if all the associated systems work together to perform to design specification. All these efforts made with systems aim to satisfy the overall performance requirements, which are part of the user requirements. These 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.

1.1.2 Role of aircraft assembly planning

The importance of aircraft assembly line design is acknowledged in the literature and recognised as part of the product industrialization (Mas et al., 2013; Ortegón et al., 2017; Ríos, Mas and Menéndez, 2012a). Assembly process planning is part of the assembly line design in this industrialization phase, which translates the product design information into manufacturing language. It defines the product assembly sequencing, and is documented in the form of assembly plans. Assembly process planning 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 functions of complex systems; secondly, integration of operations management related activities to support assembly line balancing (Li and Lockett, 2017; Scallan, 2003). The two aspects are interconnected and taken place in an iterative working manner through different development phases.

1.1.3 Difficulty of aircraft complex systems assembly planning

Aircraft "final assembly lines are organised in a similar manner by stations, each performing a specific task in the aircraft's assembly and systems testing" (Airbus, 2014). For example, A320 final assembly process includes fuselages and wing joining, systems integration in bays, cabin installation and functional tests. Academia has previously suggested that assembly related activities be taken into account as early as possible in the product design cycle, because it is costly to change design in production and will make assembly process planning difficult (Boothroyd, Dewhurst and Knight, 2011; INCOSE, 2015). However, in practice the aircraft industry is trying to reduce design changes in detailed design and series production phases (Pardessus, 2004). 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 (United States Government Accountability Office, 2011, 2012, 2013). 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. Surveys show that many similar commercial and military aircraft projects are over cost, over budget and thus do not meet customer requirement (Burge, 2010; Milner, Volas and Sanders, 2013). Traditional assembly process planning is a mostly experience-based work with general principles like "first structure then systems" and "first installation then test". The decision making of aircraft assembly precedence, in terms of installation and test sequences, is normally considered as the domain of the assembly expert (Wang, 1997). The experience-based approach does not deal with aircraft interdependencies from product data directly, which makes it difficult to generate the assembly precedence of complex systems. To ease this situation, the aircraft assembly process planning needs to be more integrated and connected with product design. Then, process planning will transfer and allocate aircraft design specifications to assembly processes and documentations.

1.1.4 Engineering data sources

Engineering data sources are the inputs of aircraft assembly planning. In the aircraft industry, 3D CAD systems have been widely used in aircraft design and manufacturing. In digital manufacturing, 3D assembly models are considered as the single source of product data in assembly process planning (Bing et al., 2009; Shen, 2006; Xiao, Duan and Zhang, 2018; Younus, Jian and Yuqing, 2010). In figure 1-1, each colour represents one major aircraft system. It shows a typical example of aircraft systems assembly model in CATIA V5. This example illustrates clearly the large number of system components from different aircraft systems in a spatial view. A limitation of 3D CAD models is that they contain only physical data and do not provide information about the functional behaviour of the components.

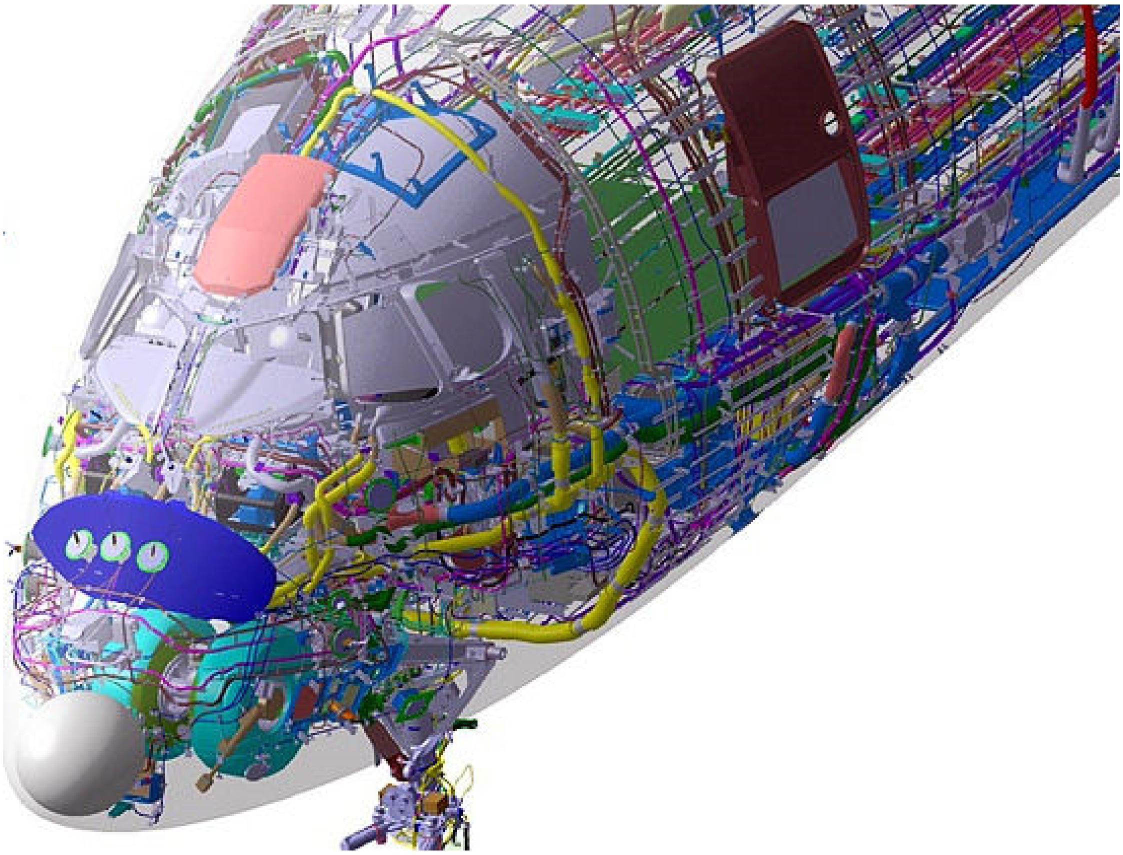


Figure 1-1 Example of aircraft system assembly model as engineering data source (The Flying Engineer, 2013)

In addition to the 3D assembly models, the system schematics are also the main engineering data sources that are used in design, assembly and maintenance services. As aircraft systems are organised in hierarchy with systems and sub-systems, system functions and dependencies are presented in different levels of schematics. System schematics define the functional behaviour and connectivity between systems but they are poor in location of system components in an aircraft.

Figure 1-2 shows the schematic of Boeing 747 electrical power distribution sub-system. It is usually used to help assembly planner to understand the functional aspect of installed system components. It also supports arranging system installation and test plans.

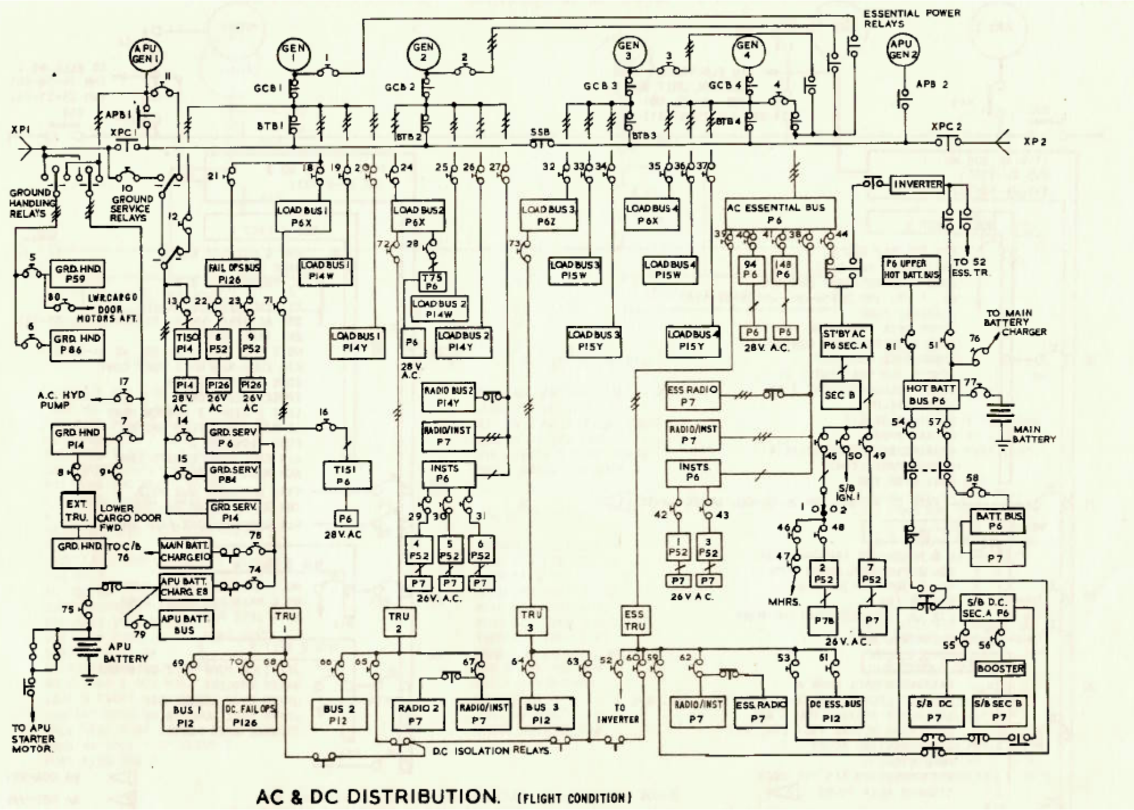


Figure 1-2 Boeing 747 electrical power distribution schematic (British Airways, 1978)

The assembly 3D models are not directly linked to system schematics. It is easy to see that in use of these engineering data sources, assembly planners need to have sufficient knowledge and experience of aircraft systems and structures to connect them manually. They have to then produce the installation and test sequences based on their personal experience. Thus, there is a need to develop a method to help assembly engineers better understand aircraft system complexities from engineering data sources and generate aircraft system assembly processes.

1.1.5 Product life-cycle management in manufacturing

The engineering data sources are controlled and managed in a product life-cycle management (PLM) system. It is an information processing system that integrates the functions of the whole company through connecting, integrating and controlling the business processes and product data (Saaksvuori, 2005). PLM systems have been used in aerospace manufacturers for many years, from early “in-house application” to current “software as a service (SaaS)” mode (Mas et al., 2015). In other words, PLM is now not restricted to only specific areas of business processes, such as aircraft design and development. The computer-aided applications (CAX) are now integrated as part of the PLM service. The product lifespan data can be more integrated in a PLM system under the SaaS mode, which is an opportunity for the integration of functional and physical design information in the same system. However, these existing tools are not being used in an integrated way to support assembly planning.

1.2 Research hypothesis

It is widely accepted that Systems Engineering (SE) principles are the typical method for solving the issues in complex product development. “SE focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal” (INCOSE, 2015). Since assembly stage is part of the product development process, a hypothesis can be defined as: could SE principles help assembly planners to better understand product design data and thus support generating more reliable installation and test processes for assembly line design? Based on this idea, this research will use the integrated CAD and SE principles to develop a method for aircraft complex systems assembly integration design.

1.3 Research aim

The research aim is to develop a method to plan the sequencing of aircraft systems installation and test at the early assembly line design stage. It will use systems engineering framework and integrated CAD to solve the complex system integration problem.

1.4 Research objectives

The research objectives are:

- To investigate the interrelationship between aircraft system design and assembly process design
- To investigate systems engineering approaches and assembly sequence planning
- To develop a method to integrate the systems engineering and assembly approaches
- To develop SE models for assembly sequencing planning
- To expand the method to include additional test related conditions analysis
- To test the developed method in two case studies

1.5 Research scope

This research concentrates on the activities of product design and assembly planning at early assembly line design stage in concurrent engineering environment, as the manufacturing decision making at this stage has great influence on later stages. However, there is no basis for detailed assembly line balancing and throughput prediction without a competently designed assembly sequence. The priority task of early assembly line design is that to generate a feasible assembly sequence (Whitney, 2004). Assembly line balancing is then applied to the assembly line plan later in the aircraft product development process.

The term “final assembly” has different definition of working packages due to different aircraft specifications, manufacturing capacities, and marking strategies. To set the scope, this research assumes that most of system components can be accessed after structure joining are integrated in final assembly stage.

The term complexity in this research refers to the large number of aircraft system components, multidisciplinary of aircraft systems, system interactions and requirements. As those complexities are mostly from system aspect, this research therefore concentrates more on the aircraft systems. Specifically, the research scope includes system complexities in terms of aircraft physical and functional interdependencies, the requirement decomposition process from design to assembly integration, and the activities that support assembly line design towards complex systems.

The term integration covers a broad range of concepts, but in this project it refers to the activities and processes bring together the component, sub-systems and systems into the aircraft, and ensure the system elements together as an aircraft. At assembly stage, system integration refers mostly to the design of an integration process, and the system installation and test activities for an aircraft.

Test is “a procedure intended to establish the quality, performance, or reliability of something, especially before it is taken into widespread use” (Oxford Online Dictionary, 2019). The term test in this research is considered as a verification and validation method from SE principles. Test therefore refers to the functional integration of aircraft systems in this research. Specifically, all the aircraft system tests are classified as functional test, including airtightness test, wiring continuity test, power-on test, other factory-level functional test, and flight test. The term physical integration only refers to the components layout and installation.

The 3D engineering data source will focus on the connections and interactions between aircraft systems, sub-systems and components, while the items inside individual system components are considered as black boxes. The assembly precedence here refers to the installation and test tasks in an assembly line with certain orders or constraints.

1.6 Research publications

The research publications by the date of thesis writing are:

- Tao Li and Helen Lockett (2017), “An Investigation into the Interrelationship between Aircraft Systems and Final Assembly Process Design” is presented in the 27th CIRP Design Conference and published in Procedia CIRP Volume 60 (2017).

- Tao Li, Helen Lockett and Craig Lawson (2019), “Using Requirement-Functional-Logical-Physical models to support early assembly process planning for complex aircraft systems integration”, Journal of Manufacturing Systems (under second round review).

1.7 Thesis structure

Chapter 2 provides the literature review which introduces the main research areas in this thesis. Chapter 3 states the research methodology. Chapter 4 describes the details on how the proposed method has been developed and the method implementation environment. Chapter 5 describes the case study results and the validation of the method. The thesis provides discussions in chapter 6, and ends with conclusions in chapter 7.

2 LITERATURE REVIEW

2.1 Introduction

This chapter investigates the previous research and academic literature of this project. The review consists of the general aircraft system development process, tools that support the complex systems integration process, aircraft systems assembly and the interrelationship between systems design and assembly process planning, and the existing methods for assembly integration sequence generation. The literature review also investigates the features of current product life-cycle management packages.

2.2 Aircraft system development

Aviation industries are making great efforts all the time to develop more comfortable, efficient, reliable, intelligent and low cost aircraft. The development of aircraft systems makes a significant contribution to many of these high-level requirements which are related to advanced functions. To understand the gap in literature, it is necessary to investigate the aircraft system characteristics and current practice in development first.

2.2.1 Aircraft system design characteristics

The development of aircraft systems can be generally concluded as the implementations of the latest electrical and information technologies at the developing time. Figure 2-1 highlights some typical system characteristics of aircraft in history.

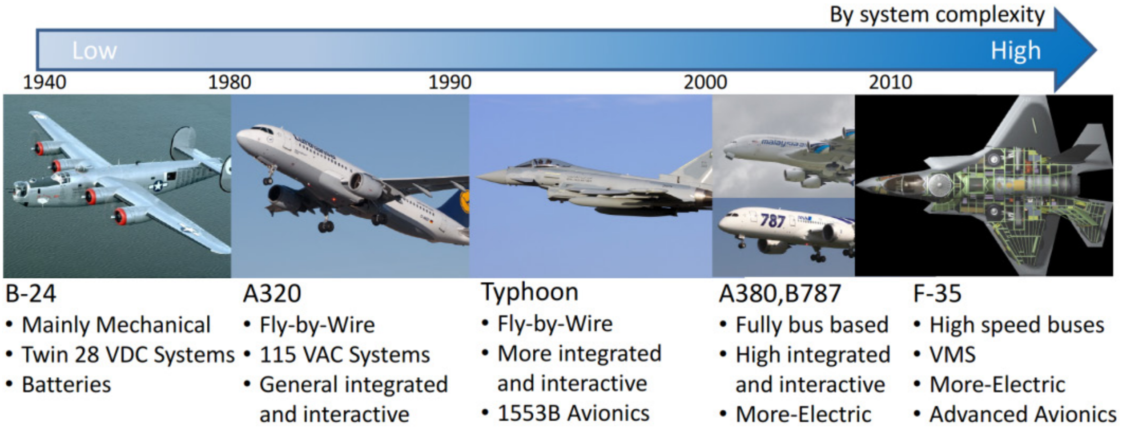


Figure 2-1 Highlights of typical aircraft system characteristics during history (aircraft photos from (Aero Icarus, 2017; All Nippon Airways, 2011; Gertler, 2018; Herzog, 2011; Lockheed Martin, 2006; Pingstone, 2008)**)**

These highlighted system characteristics from time reveal how the efforts are made to satisfy the increasing requirements. For example, the changes of electrical system indicate the aircraft have become more dependent upon electrically powered services (Moir and Seabridge, 2008). More systems equipment and components are installed in the aircraft. Aircraft requires more electrical power for advanced functions as well as more reliable and efficient power supply. Modern aircraft control surfaces are driven by digital computers using fly-by-wire technology instead of the traditional push-pull control rod system to achieve weight saving, comfortable flying and safety requirement (Moir and Seabridge, 2008; Pallett and Coyle, 1993; Tucker, 1993; Yeo, 1981). Nevertheless, these efforts ask for further system changes to ensure the introduction of the new functions. More information is collected from new sensors, and faster signal transmission methods such as high speed data bus and optical fibre technology along with new system control architectures are introduced to satisfy the system performance requirements (Collinson, 2011). All these efforts lead to the need of a high-level management system to control and manage the huge amount of interactive information between systems and sub-systems. Typical implementations in industry include aircraft information management systems (AIMS), utilities control system (UCS), vehicle management system (VMS), flight management system (FMS), integrated vehicle health management (IVHM) system (Johnson, 1993; Moir and

Seabridge, 2010; William, 2006). As a result of that, aircraft system architecture is becoming more and more integrated. The architecture design principle of using high speed data bus for interconnection is introduced to major aircraft systems and even at the aircraft level (Moir, Seabridge and Jukes, 2006, 2013; Moir and Seabridge, 2013; Pottenger, 1993).

Figure 2-2 illustrates the evolution of avionics system architectures by time. It shows clearly the system architecture changes from the old distributed controlled architecture to the popular federated and integrated control architectures today. The VMS architecture shown in figure 2-3 is another example of the implementation of more integrated system architecture. The central computers in the VMS architecture are connected with avionics and vehicle user systems through high speed data bus and interface units to control sub-systems and manage interactions between other systems (Moir and Seabridge, 2008, 2010).

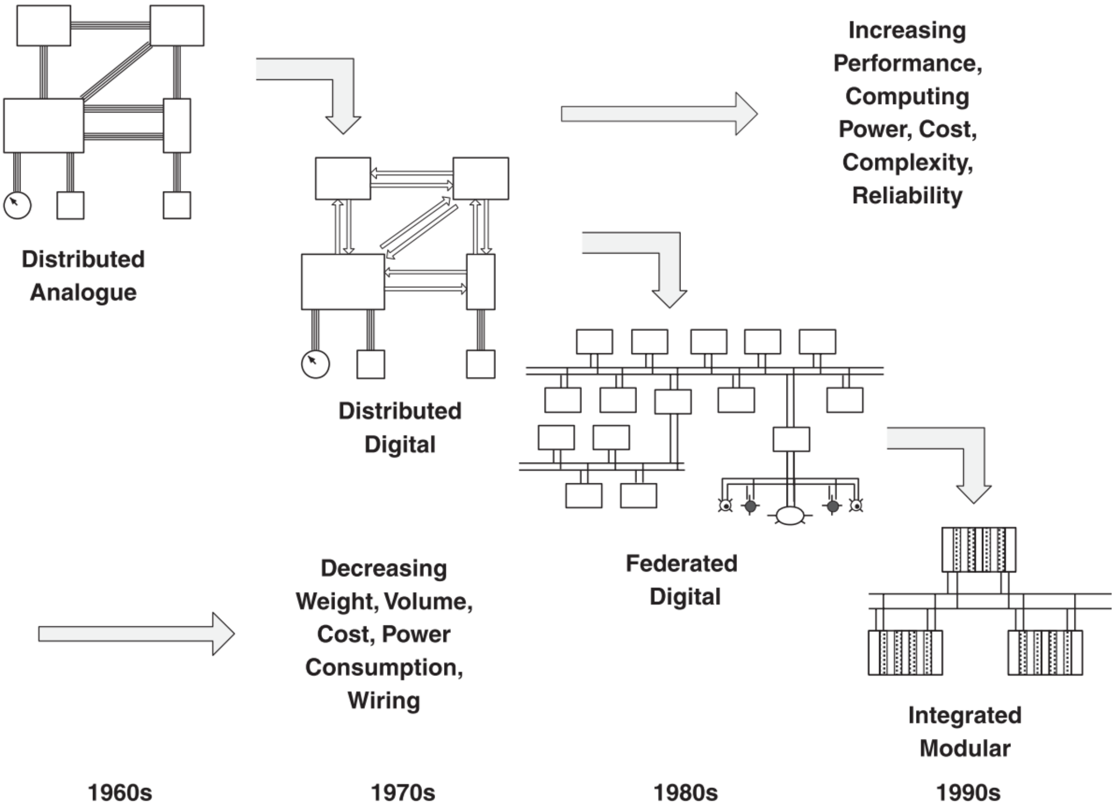


Figure 2-2 Evolution of avionics system architectures (Moir and Seabridge, 2013)

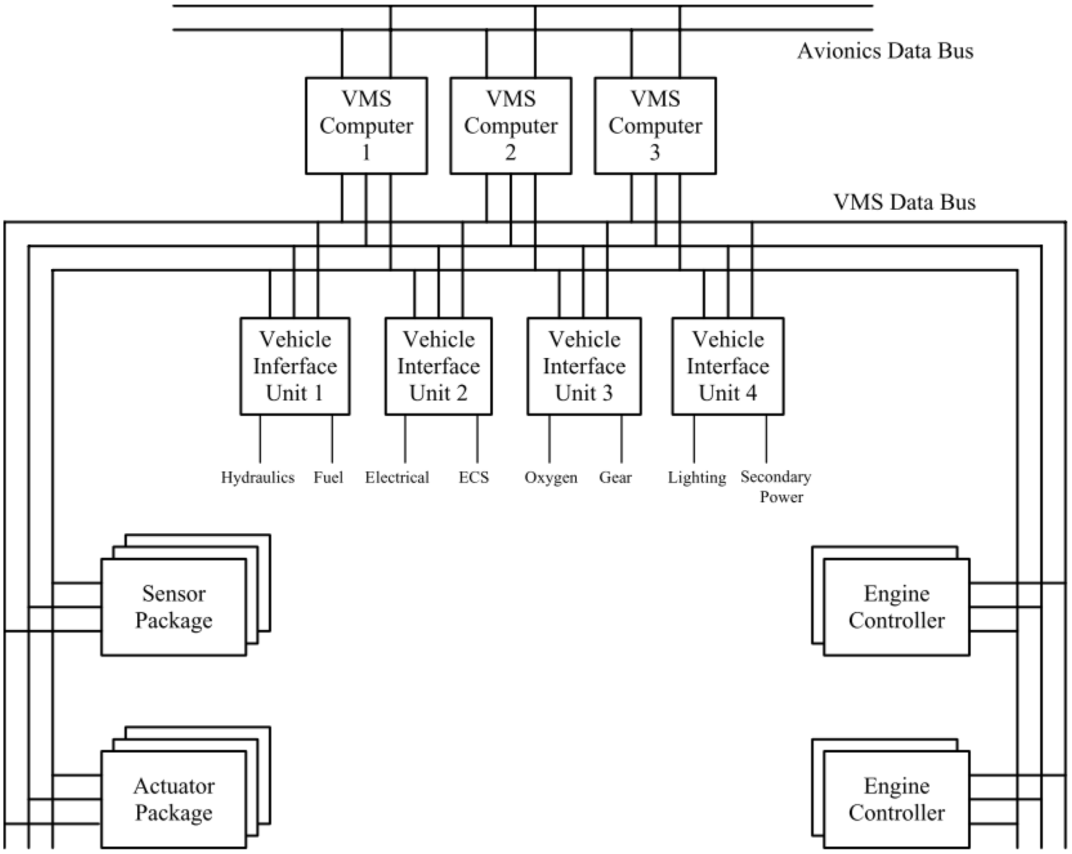


Figure 2-3 Generic VMS architecture (Moir and Seabridge, 2008)

Benefits of such system architectures include the less hard-wired wiring, less system weight, lower power consumption, more reliable working, higher system performance and easy for system expansion and maintenance. However, it also increases the system design and development complexity greatly especially the complexity of interactions between systems, which is considered as the main drawback (Moir, Seabridge and Jukes, 2006, 2013; Rechtin and Maier, 2000; Seabridge, 2010a).

2.2.2 Aircraft systems integration characteristics

It is well known that an aircraft is a system of systems (SoS) (INCOSE, 2015; Kossiakoff et al., 2011; Liu et al., 2015). The product structure of a complex system can be normally represented in a hierarchical manner (Stevens and Brook, 1998). 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. In the design and development process, multidisciplinary are applied on these systems including aerodynamics, materials, mechanical, electrical, information and computer technologies (Altfeld, 2010). Aircraft are becoming more integrated with advanced functionalities as a result of the requirements and rapid developing technologies. This leads to an increase of shared aircraft system functions and interconnectedness design (Seabridge, 2010a). There are a number of forms of system integration. Some systems like fuel tanks are physically integrated with structures (Langton et al., 2009). Some systems receive, send and exchange internal and external information for system control and display purpose (Scott, 1993; Seabridge, 2010b). Typical examples include the need of information about valves open or closed state, the display of fuel mass and engine speed, and usage of the aircrew commands (Wainwright, 1993). However, the system interdependencies can be generally concluded as two aspects which are physical and functional interdependence. According to the references from Moir and Seabridge (2013) and Seabridge (2010b), the physical aspect has strong links with weight, installation and loads, while the functional aspect is specified as information based integration. For a modern advanced aircraft, the two aspects of characteristics are shown in figure 2-4. Table 2-4 shows a brief comparison of these characteristics based on the information in figure 2-4.

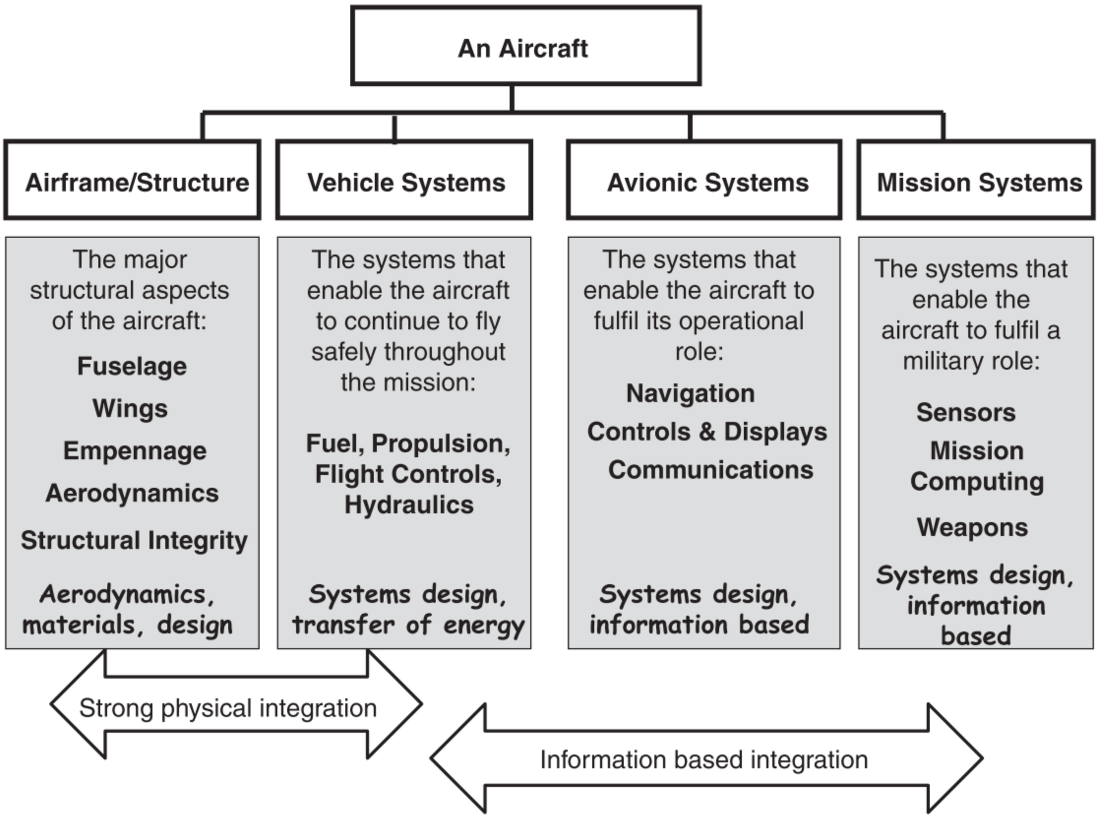


Figure 2-4 Characteristics of system integration (Moir and Seabridge, 2013; Seabridge, 2010b)

Table 2-1 Comparison of system integration characteristics based on figure 2-4

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

Physical integration is the most commonly considered characteristic in assembly (Whitney, 2004). Aircraft structural sections, system equipment and components are installed, attached and fixed through physical connections. The functional integration refers more to different power sources and information flows between systems. Vehicle systems show both strong physical and functional characteristics. Their function performing relies heavily on physical connections of other system or structural components. However, in general all the aircraft systems are still considered more as functional integration in traditional view (Linzey, 2006; Seabridge, 2010a).

2.3 System development principles and tools

Since modern aircraft development process is considered as the complex systems development, system engineering (SE) principles are introduced to solve the complex systems development problems. These principles and tools are about creating effective solutions to problems, and managing the technical complexity of the resulting developments (Kossiakoff et al., 2011; Schlager, 1956; Stevens and Brook, 1998). For example, full product life-cycle covering from beginning to the end is one of the basic SE principles, and verification and validation (V&V) ensure the product design and integration activities satisfying the requirements through the full product life-cycle. Tools are introduced in implementation of different areas. The report from National Academy of Engineering US in 2005 provides a breakdown of generic systems engineering tools for healthcare but is also applicable to engineering. In a broad sense, the systems engineering tools can be catalogued as three sections, which are the systems-design tools, systems-analysis tools, and systems-control tools (Fanjiang et al., 2005). Table 2-2 lists some typical SE tools and application area based on the author’s investigation in the aircraft sector.

It can be seen from the table that systems engineering tools cover different aspects of aircraft development from project management, engineering philosophy, quality control, detailed design, safety assessment, simulation and operations management. As the research scope focuses on how system design information would be used to support assembly planning, the systems-design tools are more relevant than systems-analysis and systems-control tools. The systems-control tools are used in the operations of an assembly line, which is the later stage of product development. However, as the systems-analysis tools like ZSA are used in system design and product prototyping (Caldwell and

Merdgen, 1991; Chen and Fielding, 2018; Chiesa et al., 2013), the design and analysis tools will be both investigated in the literature review.

Table 2-2 Typical systems engineering tools and application area (concluded based on the information from (Fanjiang et al., 2005; Kossiakoff et al., 2011; Stevens and Brook, 1998)**)**

Section	Tool	Application area
Systems-design	Concurrent engineering/product life-cycle tools	Project management, team building, information sharing
	Design structure matrix (DSM)	Dependency and interaction management and optimization
	Quality functional deployment (QFD)	Requirement capture and track between customer needs and design elements
	Functional block diagram/Function tree	Functional flow/hierarchy design
	3D CAD modelling tool (part of digital manufacturing)	3D geometry design, product modelling
Systems-analysis	Safety assessment tool from SAE ARP4761, Zonal Safety Analysis (ZSA)	Hazard analysis, safety engineering
	SE Simulation tools	System dynamic behaviour analysis/ performance analysis
Systems-control	Lean manufacturing (a set of tools)	Production control/supply chain control
	Six Sigma (a set of tools)	Design and manufacturing quality control

2.3.1 Aircraft development life-cycle tools

Modern large-scaled aircrafts are long life complex systems following by system integration and validation (Ulrich, 2008). Life-cycle is quite helpful for people to understand the progress of aircraft development and make relevant decisions to satisfy the project requirements. A life-cycle model is defined by many standards organizations, engineering communities and governments, resulting no single life-cycle model is accepted worldwide and fits every possible situation (Kossiakoff et al., 2011). Generally, the following definitions are used mostly:

- For generic system and software life-cycle: International Standard ISO/IEC/IEEE 15288-2008 Systems and Software Engineering - System Life Cycle Processes (ISO/IEC/IEEE, 2015), and EIA Standard ANSI/EIA-632-2003 Processes for Engineering a System (ANSI/EIA, 2003).
- For military aircraft life-cycle: The Department of Defense Acquisition Management model DoD 5000.02 (USA DoD, 2015), and Military Standard MIL-STD 499B Systems Engineering Model (USA DoD, 1994).
- For civil aircraft life-cycle: SAE Aerospace Recommended Practice: Guidelines for Development of Civil Aircraft and Systems ARP4754A (Society of Automotive Engineers, 2010)
- For NASA project life-cycle: NASA Programme/Project Life-cycle Model (NASA, 2007).

These life-cycle definitions vary from different development concerns and project management. Moir and Seabridge (2008, 2013) give a simplified aircraft development life-cycle model in their books, which covers from definition, design, build, test, operate to refurbish or retire (as shown in figure 2-5). It should be pointed out the test phase here refers the aircraft flight test in most cases, because there are different tests involved in other development stages such as design prototype tests, production tests and maintenance tests in operations (Drysdale, 2010; Plankl, 2015; Seabridge, 2010a).

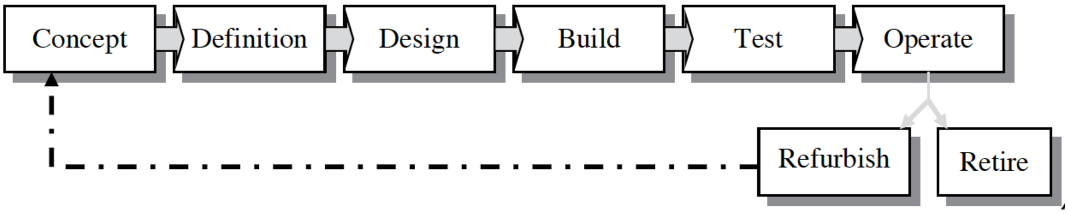


Figure 2-5 The aircraft full life-cycle (Moir and Seabridge, 2008, 2013)

The life-cycle model from SAE ARP4754A concentrates more on the activities in system development stages. In figure 2-6, the model includes three major stages: the concept, development, and production/operation. At concept phase, it defines aircraft overall requirements, specifications and configurations. This phase also investigates and proposes the possible new technologies that would be used in design and manufacturing. This phase sometimes is sub-divided into conceptual design and preliminary design phase depends on different project management. The system development phase consists of the detailed design of system function, architecture and other engineering information, and these activities work in an iterated manner allowing review and feedback to function design. The development phase ends once the build/test information is provided to the production facilities (Society of Automotive Engineers, 2010).

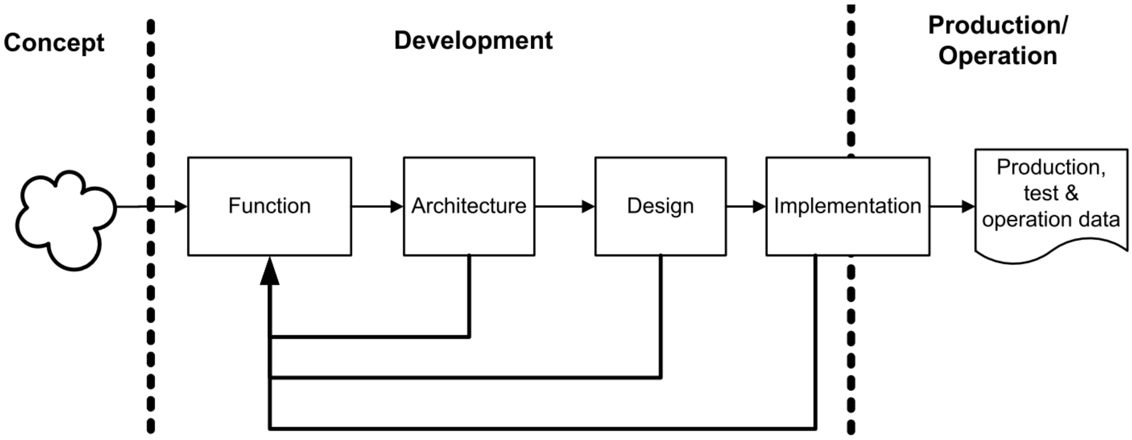


Figure 2-6 Aircraft system development life-cycle (Society of Automotive Engineers, 2010)

In practice, Mas et al., (2013) introduce that Airbus defined its development milestones in the full product life-cycle model in a concurrent way along with assembly line design stages (see figure 2-7). In the Airbus model, the aircraft product design and assembly line design has close relationship, and both of them have similar stages which are concept, definition and development. The assembly line design starts with the milestone M3 based on the definition of basic aircraft concept, and ends at milestone M9 “begin final assembly”. This model ensures the engineering data shared between product design and assembly line design, which better transfers the requirements to the later assembly activities through the “as specified”, “as designed”, “as planned”, “as prepared” process. It is clear that assembly line design is part of the product industrialization process.

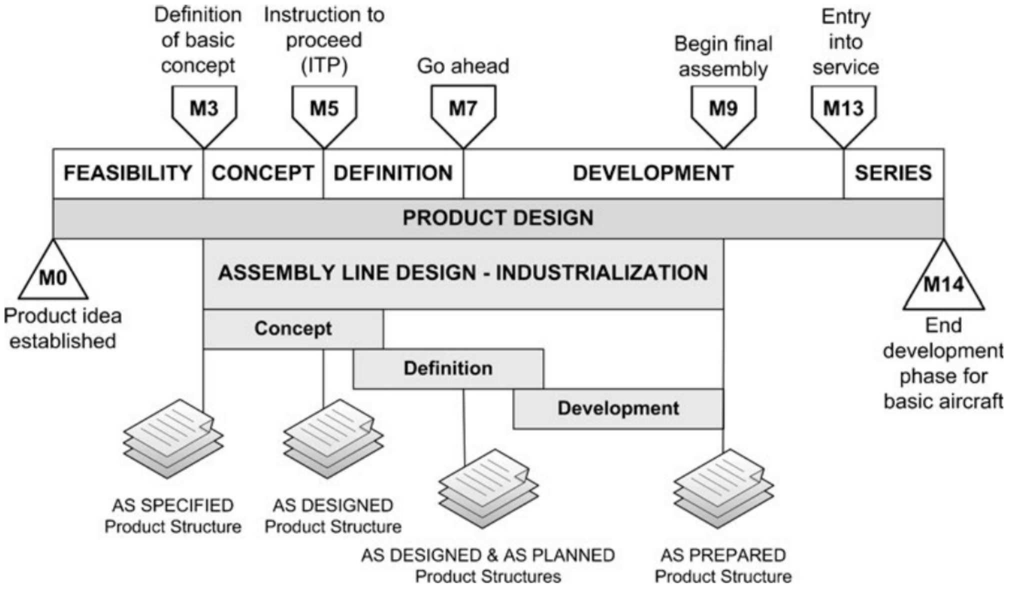


Figure 2-7 Airbus product development life-cycle model and milestones (Mas et al., 2013)

The ‘V’ model tool is another tool used to represent the system development life-cycle. It is used to describe the activities to be performed and the stage results that have to be produced during the overall system development process. It is normally used with the series product life-cycle model when combining the SE V&V principles. Moir and Seabridge (2013) present a system development ‘V’ model from Parker Hannifin, which is associated with production and includes life-cycle mile stones at the top level (see figure 2-8). It shows clearly how the requirements are decomposed from aircraft level to system level and the final (Line Replaceable Unit) LRU equipment. The systems are associated with requirement decomposition, integrations and verifications in the ‘V’ model, when project moves from contract award to the production phase.

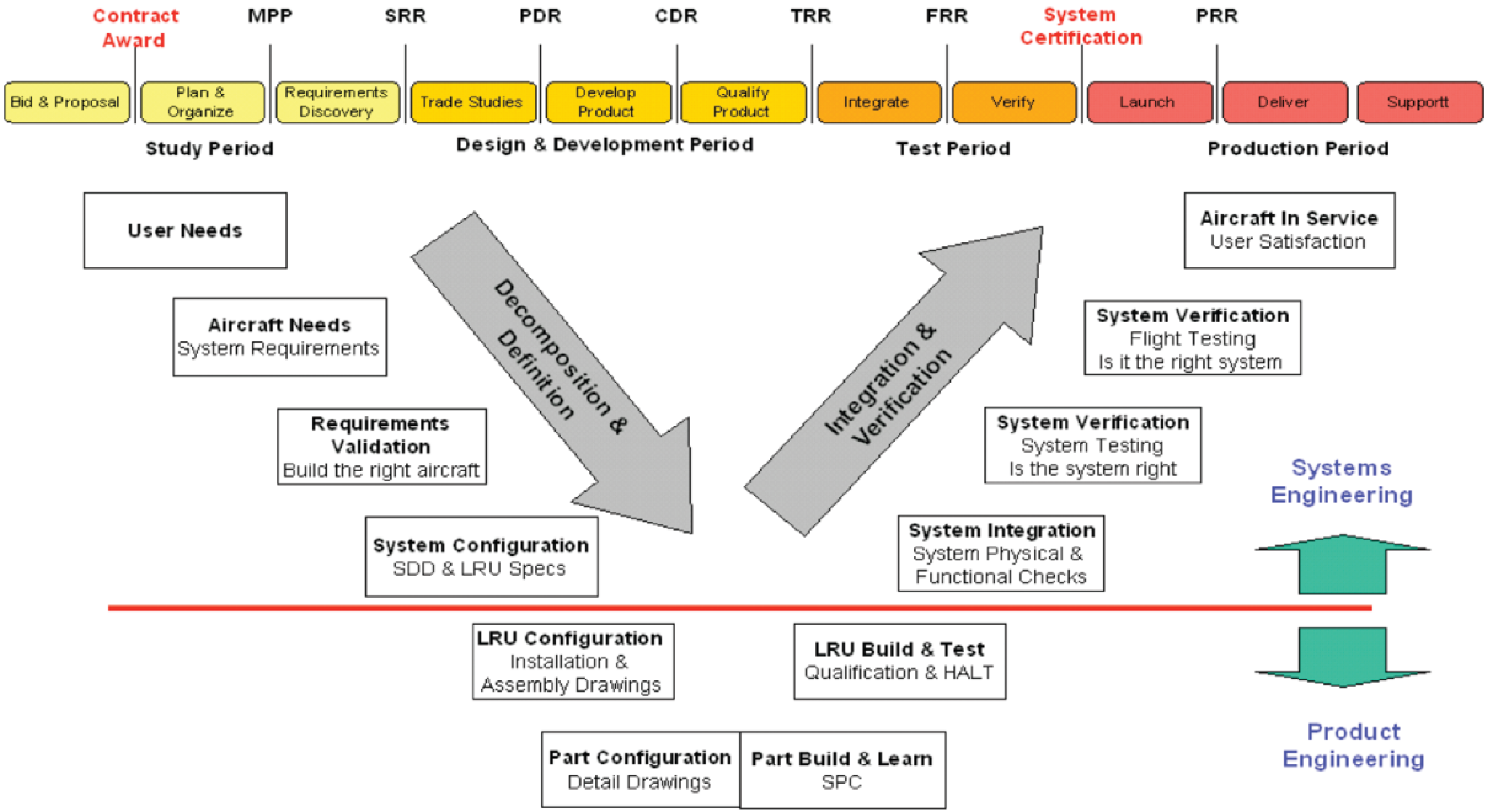
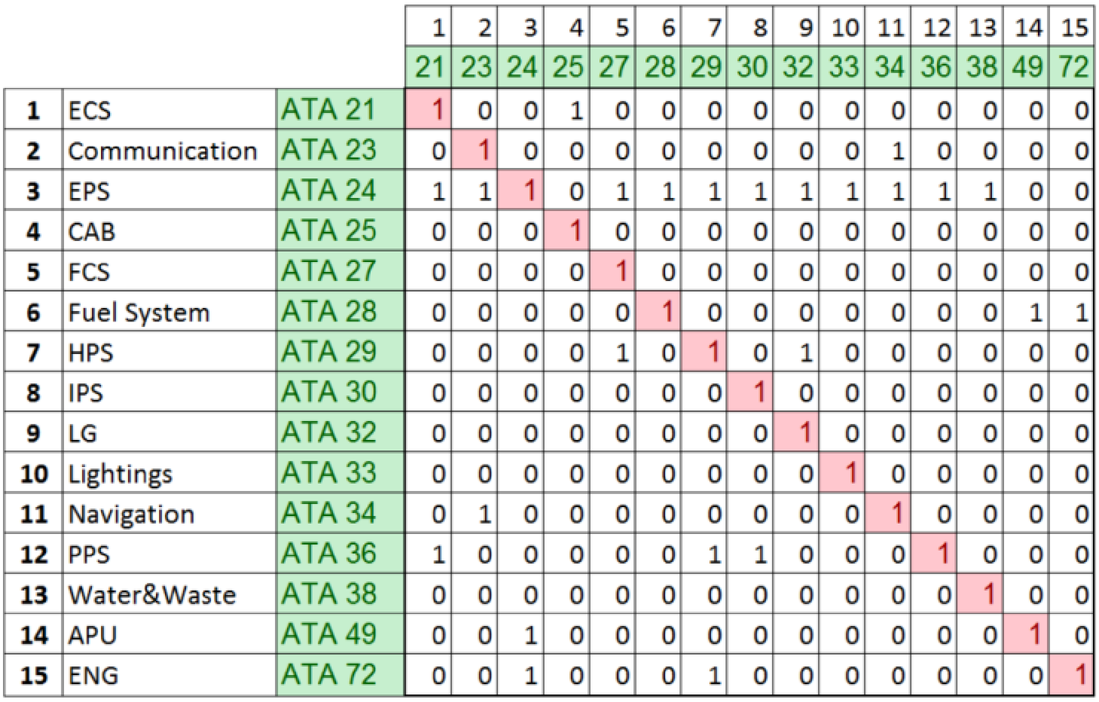


Figure 2-8 Aircraft system development life-cycle and activities (Moir and Seabridge, 2013)

2.3.2 Design structure matrix

Design structure matrix has been used in practice more than 30 years, which is a 2D matrix and information-flow oriented representation of the structural or functional dependencies of complex systems including products, processes and organisations (Eppinger et al., 2012). In the history, DSM has several synonyms or pseudonyms, including “Design Structure Matrix”, “N-squared Diagram”, “Dependency Structure Matrix”, etc (Burge, 2011; NASA, 2007; Weck, 2015). They are actually only different in implementation areas and industries. The system elements in a classic DSM represent the interactions between the labelled items in rows and columns. The advantages of this tool include the capacity of representing a large number of system elements and corresponding relationships in a more compact way, and opportunities to optimize DSM data through matrix-based analysis algorithm (Browning, 2001). DSM supports representing system interactions in a matrix of matrices way (Huang et al., 2015; Jefferson, Benardos and Ratchev, 2015), and the CAM (Cambridge Advanced Modeller) tool from Cambridge University is a free research software that provides interchangeable diagram, DSM modelling and network view function (Wynn et al., 2010; Wynn, Nair and Clarkson, 2009). An example of DSM used in aircraft system interaction modelling from Bile et al., (2018) is shown in figure 2-9.



			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			21	23	24	25	27	28	29	30	32	33	34	36	38	49	72
1	ECS	ATA 21	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2	Communication	ATA 23	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
3	EPS	ATA 24	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0
4	CAB	ATA 25	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
5	FCS	ATA 27	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
6	Fuel System	ATA 28	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
7	HPS	ATA 29	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0
8	IPS	ATA 30	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
9	LG	ATA 32	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
10	Lightings	ATA 33	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
11	Navigation	ATA 34	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
12	PPS	ATA 36	1	0	0	0	0	0	1	1	0	0	0	1	0	0	0
13	Water&Waste	ATA 38	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
14	APU	ATA 49	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
15	ENG	ATA 72	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1

Figure 2-9 Example of aircraft system interactions modelling in DSM (Bile et al., 2018)

This example represents the interactions of aircraft airframe systems in the matrix which will be used as basis for further system sizing optimization. The possibility of supporting system assembly sequence generation will be examined in a brief test in chapter 3.

2.3.3 Quality function deployment

Quality function deployment (QFD) is another matrix tool that captures customer requirements and translates those needs into characteristics about a product or service through the product development. It is expected to have a better understanding of customer needs by documenting product definition based on customer requirements at the beginning, thus improve the introduction to production and organisation on development projects through the requirement deployment process to the shop floor production control (Akao, 1988). Later in 1990s, a four phases QFD approach developed by American Supplier Institute (ASI) is introduced, which includes product planning, part deployment, process planning and production planning (see figure 2-10) (ReVelle, Moran and Cox, 1998). The quality management organisation GOAL/QPC expanded the four-phase matrix to thirty-matrix chart for more detailed deployment (King, 1989).

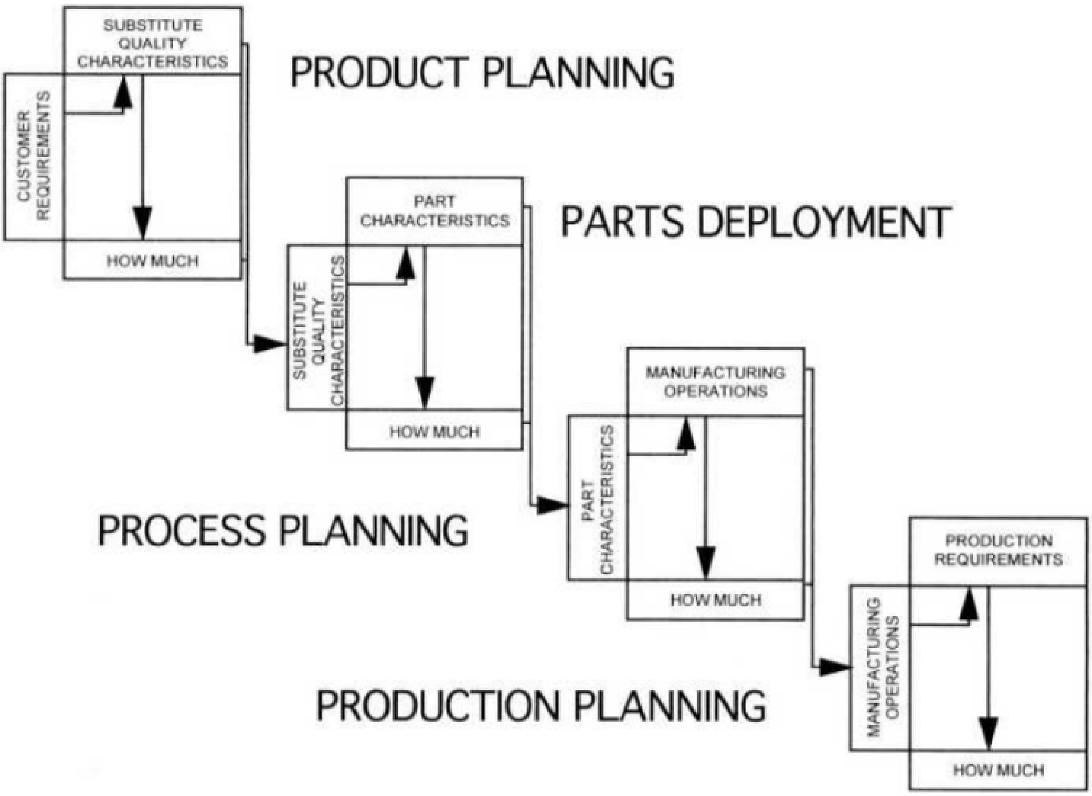


Figure 2-10 Four-phase QFD approach (ReVelle, Moran and Cox, 1998)

In the QFD deployment process, the dependencies are decided in the matrix manually by importance rating in index numbers that arbitrarily identify the rows and columns (Brown, 1991). This could help to find the key relationships of each development phase and benefit from transforming the highlighted most important interactions in the overall process. The first QFD stage is the most used matrix which is known as House of Quality (HoD) (Ficalora and Cohen, 2009). Actually, QFD does not define the product interactions but represents them using existing knowledge. This is why in practice, the QFD approach is combined with other tools such as DSM, FMEA and Fuzzy sets in implementation (Holley, Yannou and Jankovic, 2010; Jia and Bai, 2011; Liu, 2009; Moubachir and Bouami, 2015; Sharma, Rawani and Barahate, 2008). However, the problems of QFD include (Bouchereau and Rowlands, 2000; Dale et al., 1998; Kathawala and Motwani, 1994; Prasad, 2000; Rowlands and Bouchereau, 1999):

- Huge data matrixes if includes all the product interactions thus not easy to let changes during development process
- Long developing time of a full QFD chart for all the phases
- Difficulty to balance the customer demands and technical properties

These problems result in many researchers and industrial users only use the first deployment matrix HoQ. However, the idea of deploying requirements to final production control plans through several interconnected matrices is valuable for this research. The items in the QFD matrices can be traced forward and backward, which means an assembly plan in the final matrix is actually associated with the requirements in the first matrix. In addition, the expanding of four-phase QFD to detailed thirty-matrix QFD provides the possibility to adapt the QFD diagram to support aircraft system integration design and generate the sequence.

2.3.4 Functional block diagram

A functional block diagram describes the system functions and interrelationships between systems and sub-systems. It normally includes the input and output of a block connected with arrow lines. Figure 2-11 shows an example of 2D functional block diagram, or also known as system schematics.

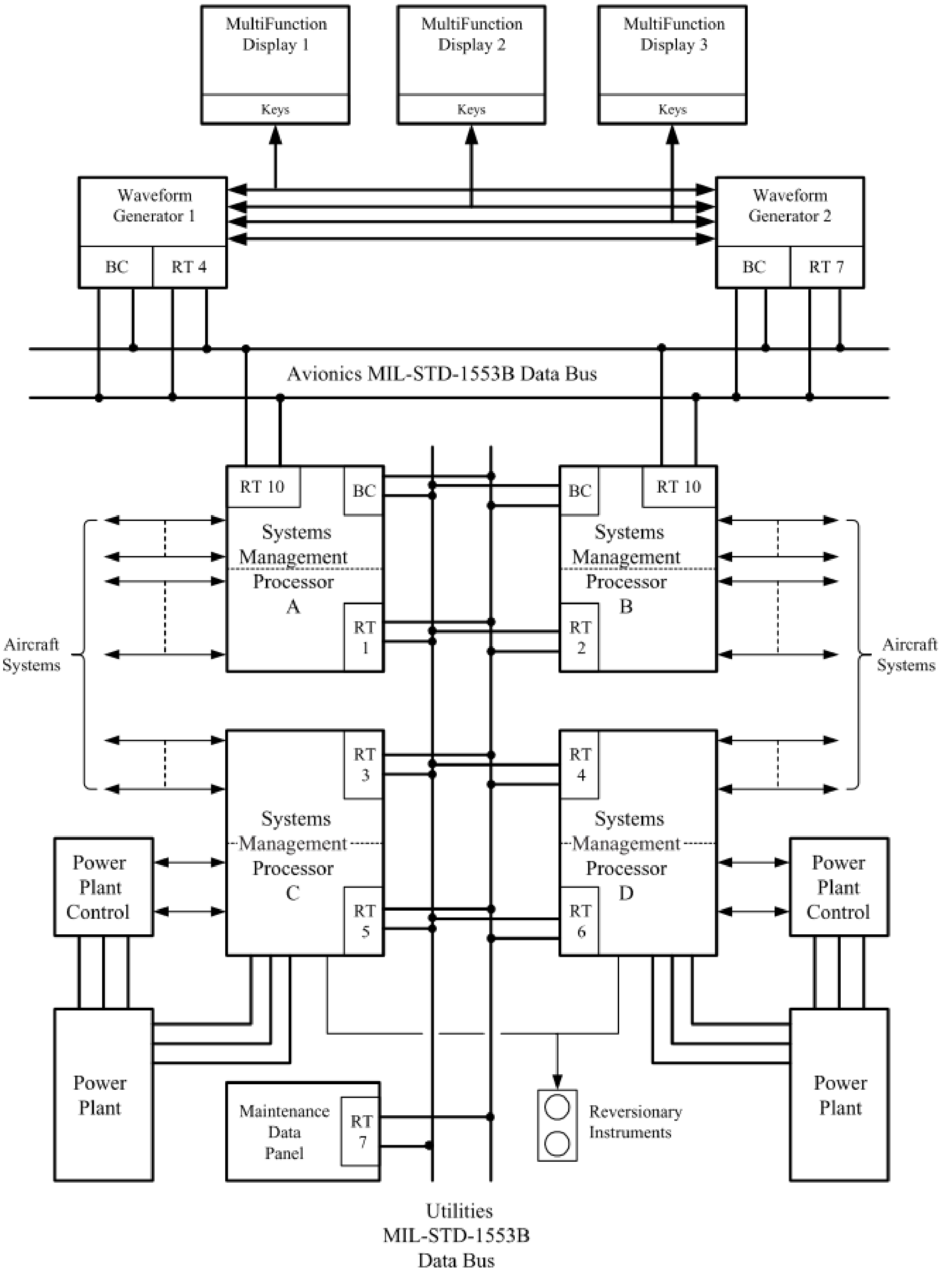


Figure 2-11 Example of 2D functional block diagram in aircraft system design (Moir and Seabridge, 2008, 2010)

It is easy for people to understand the system functions and product logical structure in one view. For instance, the information in figure 2-11 shows the aircraft system management architecture that vehicle system management processors use utilities data bus to connect the utilities, and display utility working states to multifunction displays through avionics data bus. It is also clear from the schematic that there are power supply units for the processors. The system architecture is the federated digital architecture with redundant design. However, the schematics do not give the component location information which is another aspect that assembly planning needed. Assembly process engineers cannot link the items in 2D block to physical installations directly. Sometimes, the items presenting in the schematic may be included in one system component or a set of finished products.

2.3.5 3D CAD modelling tool

In aircraft industry, Computer Aided Design (CAD) is part of the digital manufacturing widely used today to support aircraft design. It allows creating, modifying, analysing the product design effectively in software environment, and thus improving the productivity (A. Delchambre, 1996). The CAD tool is used throughout the development process from conceptual design to manufacturing. Traditionally, 3D CAD models are the design results of physical components, but many CAE software packages expand to support performance analysis, such as thermal analysis and FEA (Finite Element Analysis). In aircraft industry, the widely used Dassault Systèmes CATIA V5 is a powerful 3D geometry modelling and assembly design tool that provides a way to define the product assembly tree and spatial interactions between parts. The most used CATIA V5 modules for assembly are the “part design” and “assembly design”. Except the geometrical information that can be defined in CATIA V5, the non-geometric information needed for manufacturing like tolerance, assembly note and other text describing technical requirements can also be defined as Product Manufacturing Information (PMI) in the solid models (see figure 2-12). Besides, CATIA V5 has very limited features of product functional modelling, such as the “Structure Functional Design” tool from the “Equipment & Systems Engineering” module, the “Product Function Definition” from the “Knowledgeware” module (Dassault Systèmes, 2009). However, these tools only define the mechanical dependencies to represent spatial interactions.

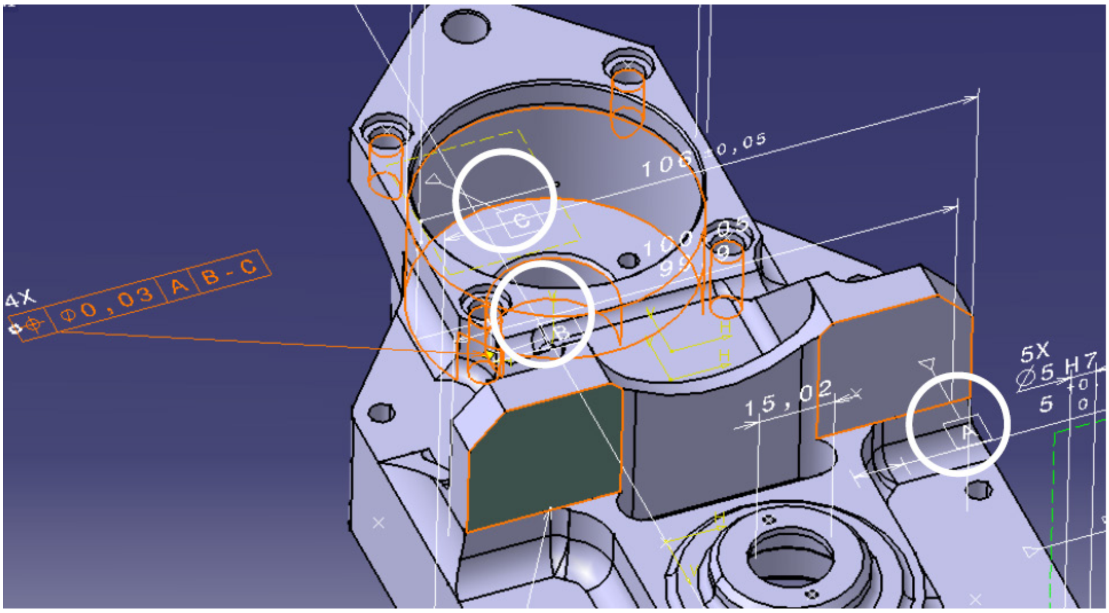
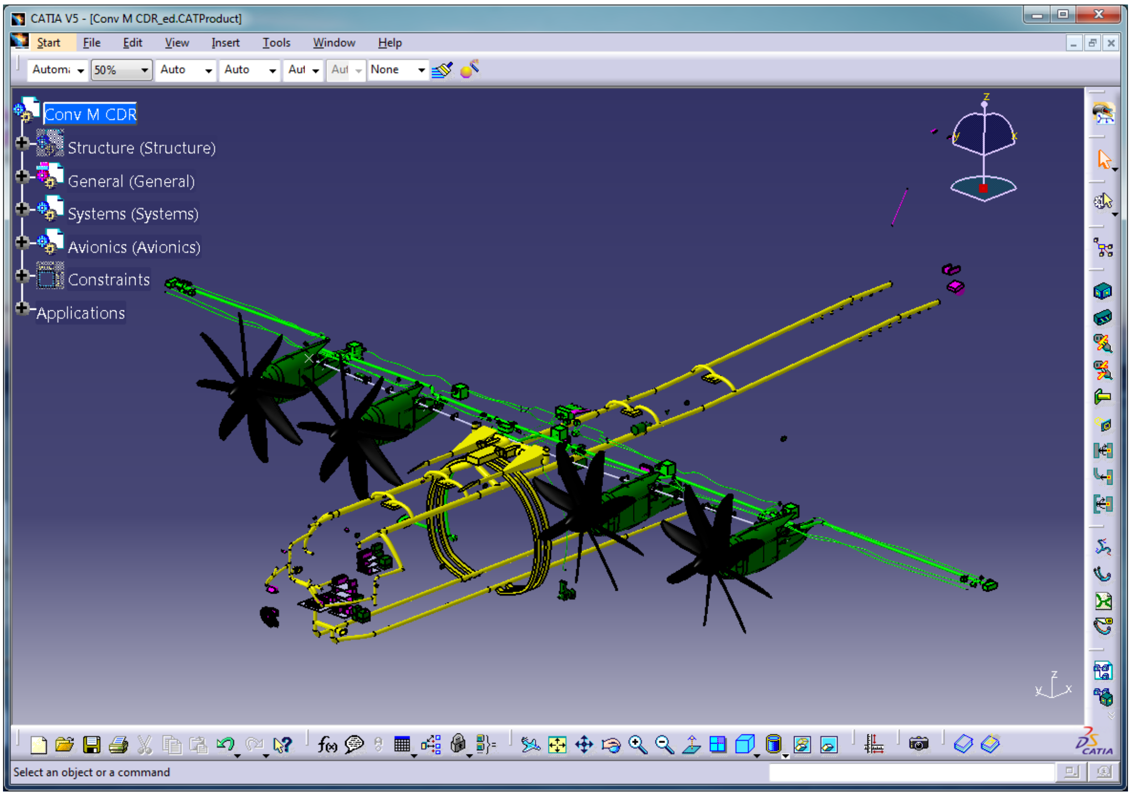


Figure 2-12 Example of PMI in CATIA V5 (Andre and Sorito, 2002)

Figure 2-13 illustrates the aircraft system assembly models in CATIA V5 including airframe and avionics systems in different colours. The structure assembly node is hidden in this figure to have a full view of installed system components. It is easy to access the physical dependencies directly from the 3D assembly models in terms of physical connection between systems, and between system components and structural parts.



Select an object or a command

Figure 2-13 Example of aircraft system 3D master geometry model in CATIA V5 (unpublished report from Cranfield University (2015)**)**

The main benefit of using 3D CAD model tool is the visualization of design, and the 3D models could be re-used as engineering data source for design analysis, manufacturing and even in maintenance (Lockett, Fletcher and Luquet, 2014). CAD tools are recommended to link with engineering information management system since 1990s (Stark, 1992). However, from the view of assembly planners, there is a still drawback in current CAD tool implementation. As modern aircraft require several system components working together to perform aircraft functions, it is not possible to specify all the functional interactions in the text-based PMI. The Computer-aided Process Planning (CAPP) is introduced for quite a long time in industry. CAPP is mostly used for automatic machining process planning. Assembly process planning in CAPP, such as Dassault Systèmes DELIMA, is still an experienced based manual work, as it needs assembly planners to link the 3D assembly components to system functions (Mas et al., 2014; Menéndez et al., 2012).

2.3.6 Safety assessment tool

Zonal Safety Analysis (ZSA) is one of the Common Cause Analysis (CCA) tools from the aircraft industrial process in SAE ARP4761 “Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment” (Society of Automotive Engineers, 1996). It is introduced to analyse how aircraft system installation of individual systems or components could mutually influence between other systems/components installed in close proximity on the aircraft. The analysis begins with the definition of zones on the aircraft, and then uses design and installation guidelines and criteria to inspect the system component installations and inference in each zone. Figure 2-14 shows the part of the zone definition of NASA N3-X aircraft. The aircraft is first divided into several major zones by major structural sections such as wing, fuselage and power plant. It is then sub-divided into further sub-major zones as cabins, bays and fairings. Inspection records are documented and submitted to relevant departments of the project for problem resolution. Analysis records are also used for resolution process tracking in regular inspections (Society of Automotive Engineers, 1996). Figure 2-15 shows the working process of ZSA. It is interesting to find that project experience, maintenance and operational hazards, and aircraft level requirements are important inputs in preparing of design and installation rules. The results from other quality control tools such as FMEA (Failure Mode and Effects Analysis) and FMES (Failure Modes and Effects) can also be used as inputs to support preparing the component list of external failure.

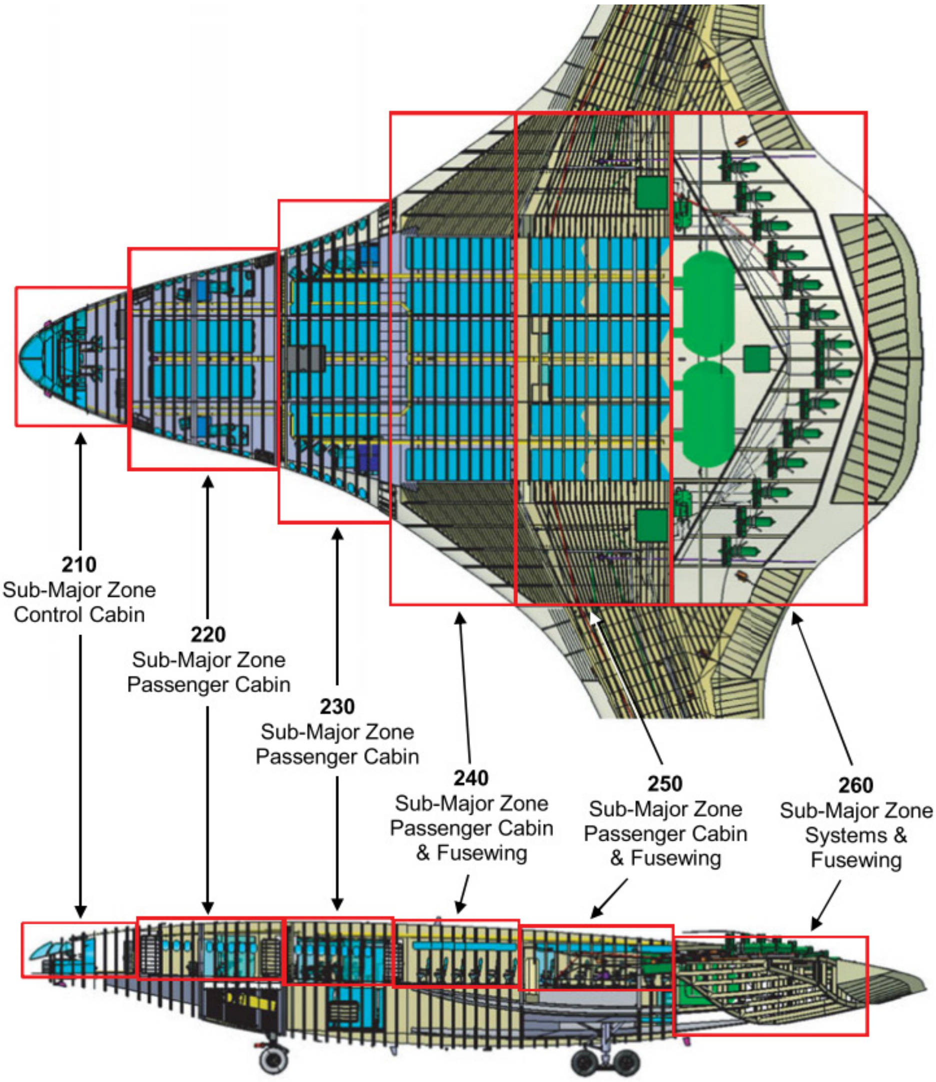


Figure 2-14 Example of zone definition (Chen and Fielding, 2018)

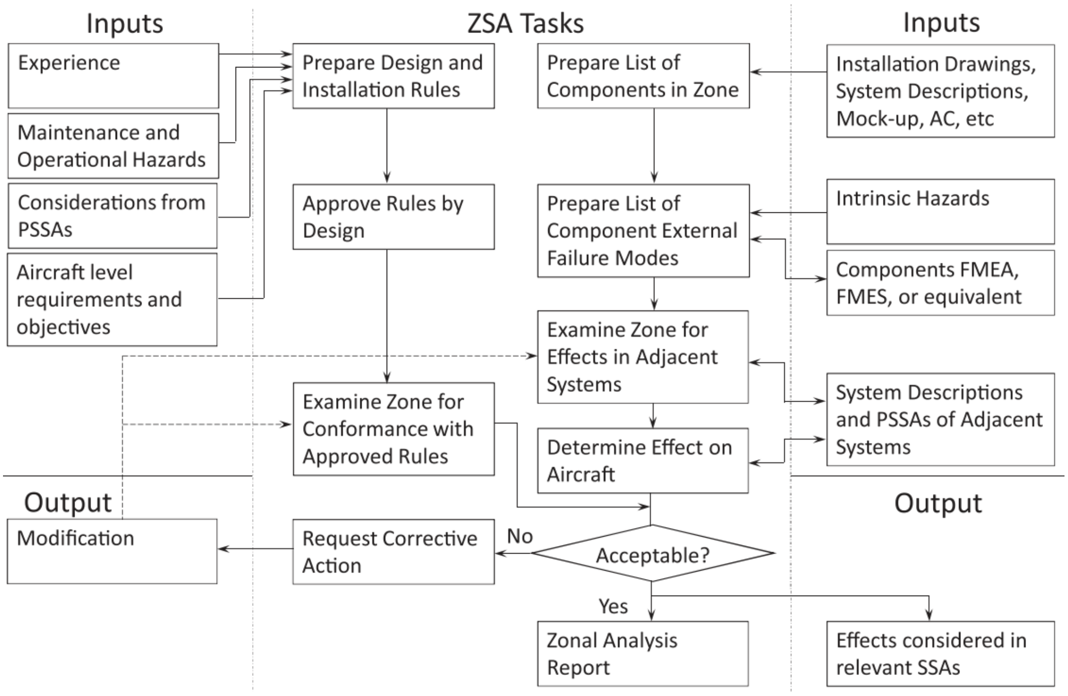


Figure 2-15 ZSA working process (Society of Automotive Engineers, 1996)

The ZSA tool considers how the locations of the system installations can affect the working of their redundancy by following guidelines and criteria from design requirement. The SAE ARP4761 guideline suggests that ZSA should be carried out during the product life-cycle (Society of Automotive Engineers, 1996). It is found in industry that ZSA is normally started after the first aircraft was well into the production line, or performed on flight testing aircraft and in-service aircraft (Caldwell and Merdgen, 1991; Harbottle, 2001; Society of Automotive Engineers, 1996). Very few researchers try to apply ZSA at conceptual design stage to select design alternatives (Chiesa et al., 2013). To ease the work in production, it is also recommended to have a preliminary ZSA on a full-scale physical prototype aircraft, or assembly drawings and 3D CAD models as the physical design matures (Caldwell and Merdgen, 1991; Hasson and Crotty, 1997). This also partly explains why ZSA mostly states the physical issues, as the design drawings and models only have physical connection and spatial information. A research report from FAA (Federal Aviation Administration) admitted that historically the safety analyses do not address EWIS (Electrical Wire Interconnect System) failure fully or at all (Linzey, 2006). This report strongly suggests functional analysis to be involved in the overall ZSA process but only in the form of wire short test. In production of jet aircraft, Boeing uses bent-pin test as part of ZSA to detect possible short to ground and bundle damage caused by improper installations (Caldwell and Merdgen, 1991). The bent pin analysis is done one pin at a time and analyses the effect on the system of pin-to-pin shorts. However, as the complexities of modern aircraft are caused by the increasing electrical systems and interactions, even if the ZSA is combined with continuity tests, it is far from enough for the verification of critical characteristics in the assembly line. To sum up, the mechanism of analysing assemblies by structural zones reduces the scope of system complexity, which makes the ZSA work easier to be done in practice.

2.3.7 SE Simulation tool

SE simulation tools are based on the Model Based Systems Engineering (MBSE) approach, which is the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life-cycle phases (Systems Engineering Vision Working Group of INCOSE, 2007). To develop a complex system, it is important to create high-level models to understand how to configure system structure and behaviour to meet system’s desired specifications. There are two generic system modelling languages: Unified Modelling Language (UML) and Systems Modelling Language (SysML). UML and SysML are both methodology and tool independent, only visual modelling language with grammar and vocabulary (Delligatti, 2013; Rumbaugh, Jacobson and Booch, 2004). For more effective and specific reason, SysML is developed by extending UML to support the specification, analysis, design, verification and validation of complex systems that include hardware, software, data, personnel, procedures and facilities (Friedenthal, Moore and Steiner, 2009). A simple SysML model is shown in Figure 2-16, which describes the sub-system function, properties and interface of a satellite solar panel.

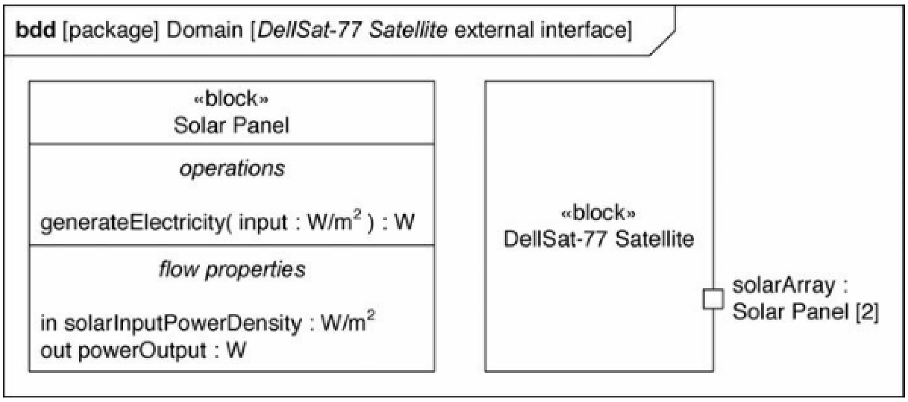


Figure 2-16 Example of SysML model (Delligatti, 2013)

Another popular simulation language tool is Modelica, which is an object-oriented, declarative modelling language covering mechanical, electrical, electronic, hydraulic, control and thermal fields. Modelica is implemented in many software packages, including the Dassault Systèmes Dymola and Siemens Simcenter Amesim. The Dymola environment is now embedded in the new version of Dassault Systèmes V6, which integrates the traditional CAD tool with dynamic simulation environment (see figure 2-17).

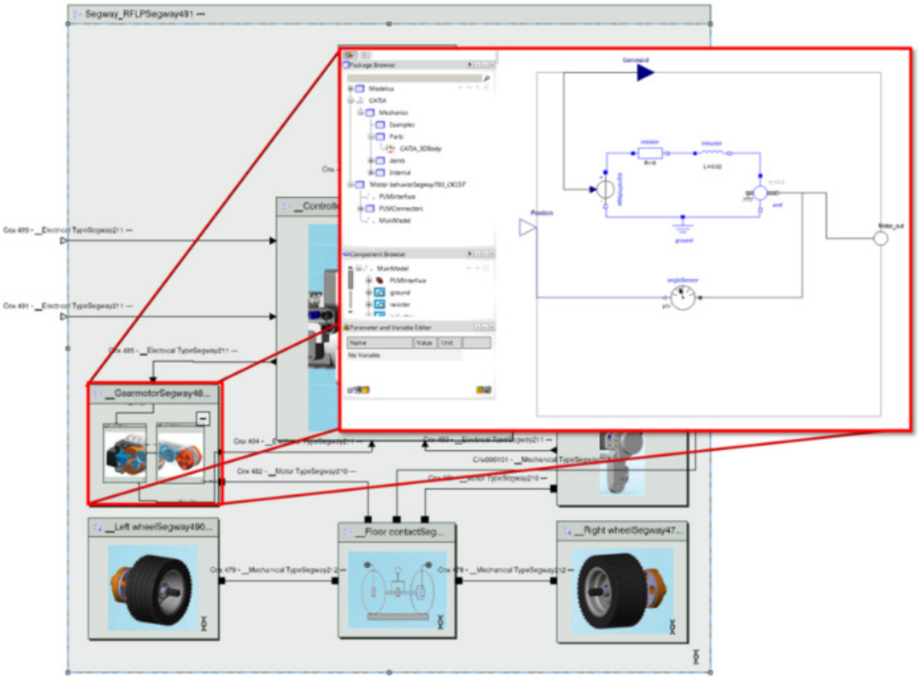


Figure 2-17 Example of system dynamic simulation in CATIA V6 Dymola package (Kleiner and Kramer, 2013)

2.4 Aircraft systems assembly

Assembly is the process of putting together a number of parts to make a machine or other product (Collins Dictionaries, 2017). This is a generic definition based on physical connections. In the aerospace sector, aircraft assembly process is described as “the airplane grows from small assemblies, and these small assemblies are made as complete as possible before moving on to the next stage” (Ashmead, 1956). As many of the system components are integrated at final assembly stage, the investigations will concentrate mainly on how systems are installed and tested through the final assembly process.

2.4.1 System assembly in final assembly process

The scope of final assembly varies from company to company and from one aircraft to another. This is mainly due to different marketing strategies, manufacturing capacities and aircraft technological specifications. Examples can be found on modern civil and military projects where major section assemblies arrive at final assembly line (FAL) with some systems installed by subcontractors or provider (Menéndez et al., 2012). Ashmead (1956) describes the Douglas A-4 aircraft final assembly process in his book 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”. For modern aircraft, the main activities and tasks in final assembly can be generally concluded as: joining major structure sections, installing systems which are not suitable for earlier stage and testing the developing and complete aircraft (Airbus, 2014; Mas et al., 2013). Figure 2-18 shows two main FAL layouts implemented in industry, which are bench layout and flow line (Baudin, 2002). Sometimes bench layout is also known as fixed-position or slant assembly (Jones and Hazlehurst, 2003), while the flow line layout consists of pulsed-line and continuous moving line. Since the flow line layout is easier for waste reduction and mass production, it is widely used in FAL today. The layout in Figure 2-18 (b) is a typical pulsed-line organized by stations and normally named with countdown numbers. As each station has an equal takt time, a continuous moving line can be treated as a pulsed-line that includes many stations of short takt time.

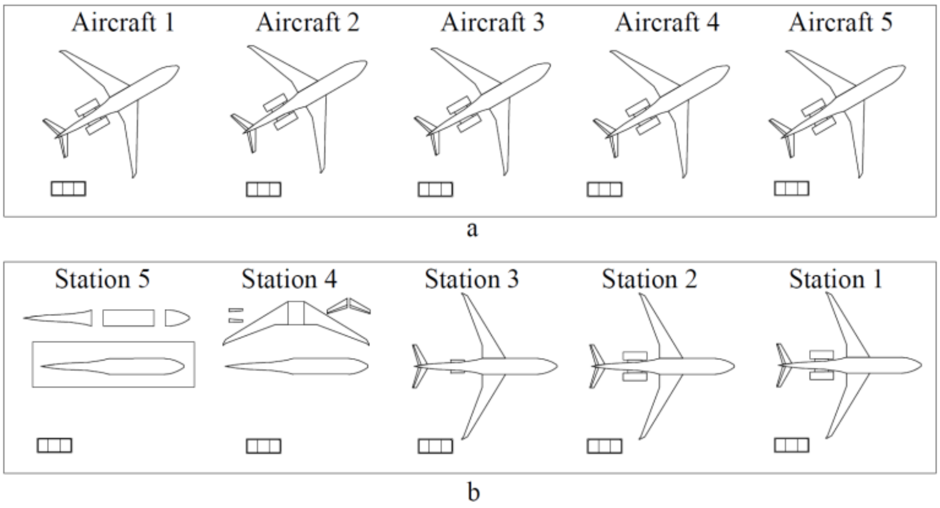


Figure 2-18 (a) Bench layout (b) Flow line layout (Li and Lockett, 2017)

Frankenberger (2007) states that in the A320 FAL at Airbus Hamburg the aircraft system equipment installation is “an enormous workload of high tech manufacturing processes”. Figure 2-19 shows the final assembly process of aircraft systems of Airbus A320. The Airbus A320 fuselage work packages include insulation blanket layout, windows and doors installation, electrical cable wiring, mechanical system lines layout, and different kind of system tests. The process illustrates how aircraft systems are integrated from brackets and fixed components on the structure, to pipes and cable harnesses and at last functional verification through multidisciplinary tests. The process also clarifies the general FAL process is from physical installations to functional tests.

In an assembly line, installation and test are the main activities. 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. Halfmann et al. (2010) 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 (see figure 2-20).

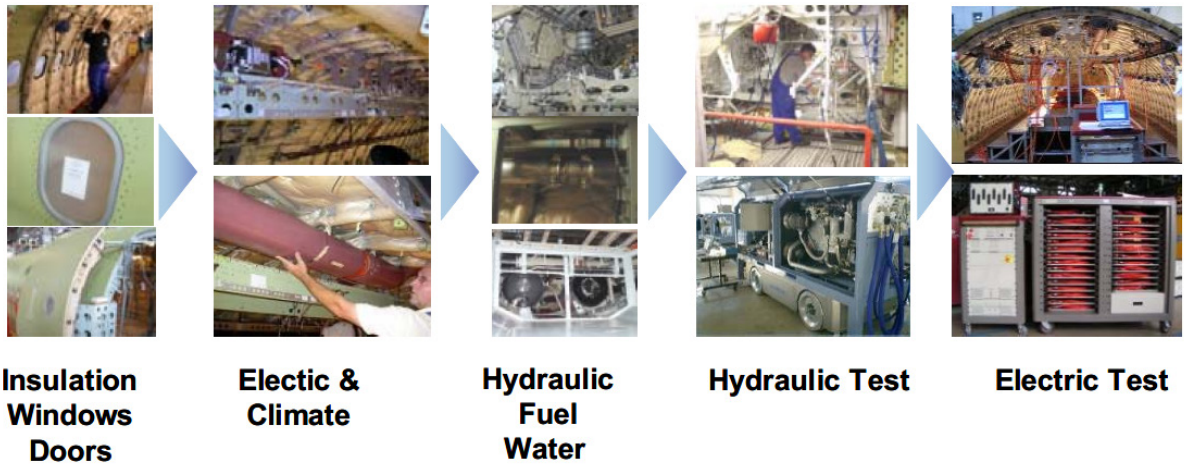
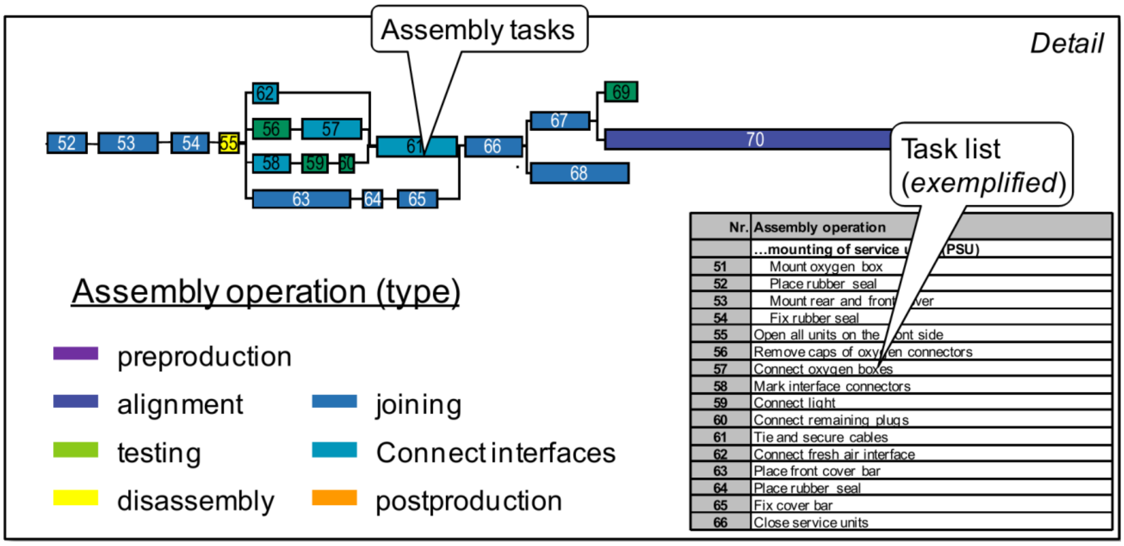


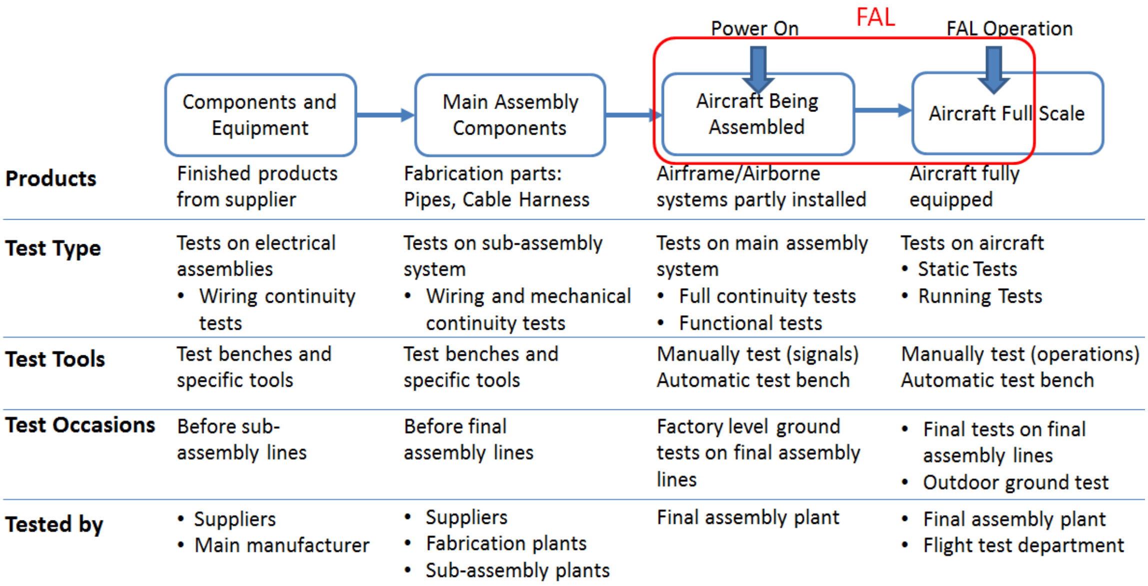
Figure 2-19 Systems integration process of Airbus A320 family in the final assembly line (Frankenberger, 2007)



Nr.	Assembly operation
	...mounting of service u (PSU)
51	Mount oxygen box
52	Place rubber seal
53	Mount rear and front ver
54	Fix rubber seal
55	Open all units on the ont side
56	Remove caps of oxy en connectors
57	Connect oxygen boxes
58	Mark interface connectors
59	Connect light
60	Connect remaining plugs
61	Tie and secure cables
62	Connect fresh air interface
63	Place front cover bar
64	Place rubber seal
65	Fix cover bar
66	Close service units

Figure 2-20 Part of the assembly priority chart of aircraft interior assembly process (Halfmann, Krause and Umlauft, 2010)

There are different kinds of test involved in the aircraft design and manufacturing process. Doumbia et al. (2009) and Plankl (2015) introduce the sequence of system test and integration of airborne systems in Airbus, which consists of the tests in specialised test labs and tests on aircraft in manufacturing and final assembly. The tests are performed in the sequence of mechanical and electrical functional test of installed components, sub-system or system functioning and performance test, and overall system test. Ashford (2004) 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. Hemmaplardh et al. (2009) take special interest in the test of electrical power system integrated 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. According to the investigations from Airbus (2014), Ashford (2004), Ashmead (1956), Caldwell and Merdgen (1991), Doumbia et al., (2009), Hemmaplardh et al., (2009), Lockett Martin (2004), and Plankl (2015), the test activities at assembly stage can be concluded in figure 2-21.



	Components and Equipment	Main Assembly Components	Aircraft Being Assembled	Aircraft Full Scale
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

Figure 2-21 Summary of system test in the manufacturing process

The summary shows the complexity of system test in the assembly process. Compared to the mechanical tests for structural assembly such as fuselage alignment and fuel tank airtightness test, the advanced aircraft system test process is actually the process of software applications on aircraft systems (Ashford, 2004). This is due to the fact that most of the advanced aircraft systems are powered by real-time digital control computers today. If considering structures and systems work in the overall process, a generic simplified relationship of installation and test in an assembly line is then concluded based on the information in figure 2-21, and illustrated in a count-down numbered work stations assembly line process (see figure 2-22). It shows the final assembly process from structural work to aircraft final check-out and delivery. As sub-systems and systems are ready to perform their designed functions through the assembly line process, more tests are arranged at later assembly line stages.

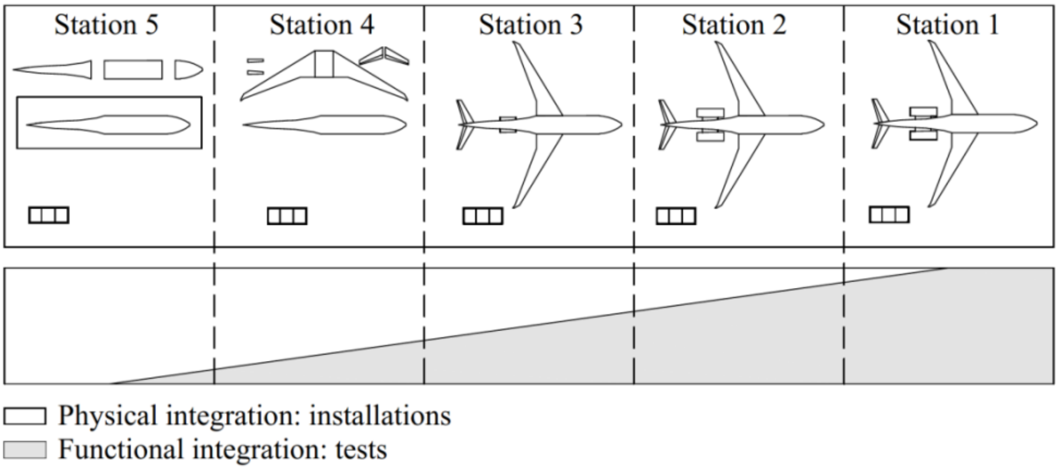


Figure 2-22 Simplified installation and test relationship in aircraft final assembly line (represented by the author based on the information in figure 2-21)

2.4.2 Relationship between installation and test in assembly integration

It is already known from the investigations in section 2.2 that physical and functional integration are the two aspects of system characteristics. Traditionally, 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 function performing rely heavily on physical connections of other systems or structural components. In a traditional view, aircraft systems are still considered more as functional integration from the aircraft level viewpoint (Linzey, 2006; Seabridge, 2010a).

The two aspects of characteristics are interdependent. In the integration process, both physical and functional characteristics have 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 system components installation at later stages. This “structure to system” sequence is the traditional image of aircraft assembly line process, which might be the assembly sequence that most previous researchers used as the baseline to carry on further work. Some researchers consider the structure join-up sequence directly as the assembly line process (Caggiano, Marzano and Teti, 2016; Gómez et al., 2016; Mas et al., 2013; Ríos, Mas and Menéndez, 2012b). Only a few researchers pay attention to the aircraft system work in assembly. However, most of them do not explain clearly the constraints and interrelationship in assembly integration, considering system assembly as a separate and additional working stage only (Frankenberger, 2007; Halfmann, Krause and Umlauft, 2010; Menéndez et al., 2012; Scott, 1994; Whitney, 2004; Ziarnetzky, Mönch and Biele, 2014). In an aircraft assembly line, the relationship between physical and functional integration is far more complicated than a serial sequence of physical structure followed by functional system. There are actually certain system pre-equipping works included in the structural section assembly for technical and operational reasons (Judt et al., 2016; Lockett, Fletcher and Luquet, 2014). 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.

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 (A. Delchambre, 1996). Aircraft designed function, especially system function, is 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” (Fritz et al., 2013). Understanding the system functions and interactions to generate feasible assembly sequence is the main challenge assembly process engineers face today.

From figure 2-21, the factory-level system functional tests include continuity test, power-on/built-in test, and functional test. The main mechanical continuity 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. Based on the relationship shown in figure 2-22, a comparison of the test timelines for different aircraft system architectures on a final assembly line is illustrated in figure 2-23 (Li and Lockett, 2017).

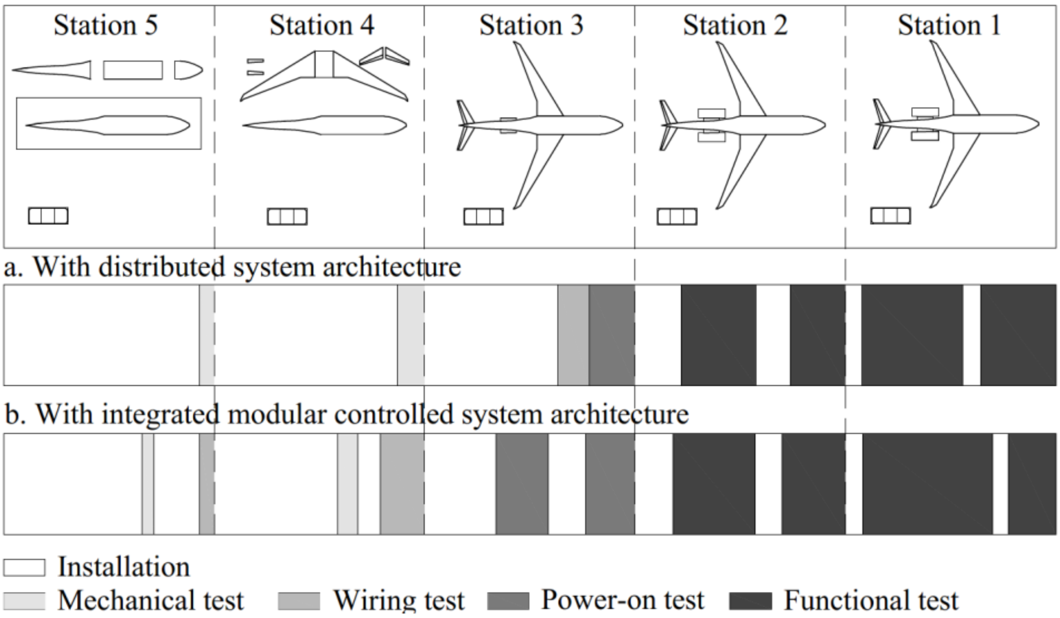


Figure 2-23 Simplified installation and test relationship with different aircraft system architecture in the final assembly process (Li and Lockett, 2017)

In figure 2-23b, more tests are found in the overall process, especially at later assembly stages when the aircraft uses the integrated modular controlled system architecture. The main reason is that many of the system functions are shared in the integrated system architecture, thus the complete installation of an individual sub-system does not mean that its function can be tested and verified immediately.

2.4.3 Assembly line installation and test from a SE view

Due to the highly complex and integrated nature of modern aircraft systems, highlighted concerns are given the possibility of development errors causing or contributing to aircraft failure conditions (Society of Automotive Engineers, 2010). Verification and validation principle is one of the SE principles used to mitigate the errors in aircraft system development process. The tests taken place in the assembly line are part of the V&V process. In fact, “in producing a complex product, integration and verification may be repeated several times” (Stevens and Brook, 1998). Two concepts from SE explain the differences between tests in design and manufacturing stage (see figure 2-24).

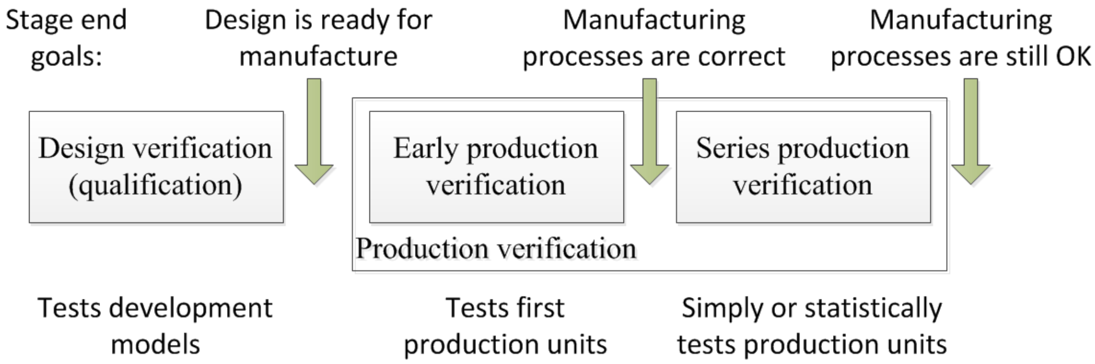


Figure 2-24 Aircraft system design verification to production verification (adapted from “mass production” to aircraft “series production” based on (Stevens and Brook, 1998))

Stevens and Brook (1998) explain the design verification certifies that the design meets the requirement, while production verification checks that the system has been manufactured correctly. Design verification tests should verify all levels of aircraft system design from modules, equipment, sub-systems to the full-scaled system in order to give clearance to manufacture operational units (Plankl, 2015). However, industry admitted that although assembly line functional test is supposed to only uncover manufacturing problems, at the early stages of rate production phase it still benefits from a completely integrated aircraft to find system software bugs (Ashford, 2004). Aircraft will be more lightly tested in series production on the assumption of no more design changes on current design. Although the two verification tests have different test strategy, they are still interconnected with the system functions and requirements. In an aircraft assembly line, the installation and test activities must guarantee a fully functional aircraft with no need for rework. What is more, the integration on an assembly line faces more realistic environmental and working conditions than the integration on an iron bird at the design stage. This means the systems integration in an assembly line may be similar to the integration process at design stage, but assembly integration should consider more constraints from manufacturing and operations.

Drysdale (2010) from BAE Systems states that the definition, design, build and test phases in Moir and Seabridge life-cycle model can be described in a ‘V’ model as concept definition, preliminary design, detailed design, validation and verification testing. This model clarifies the relationships between the top-down system design process and bottom-up integration and testing activates (see figure 2-25). The tests in the bottom-up process are used to verify the aircraft system design from equipment function to systems and aircraft functions.

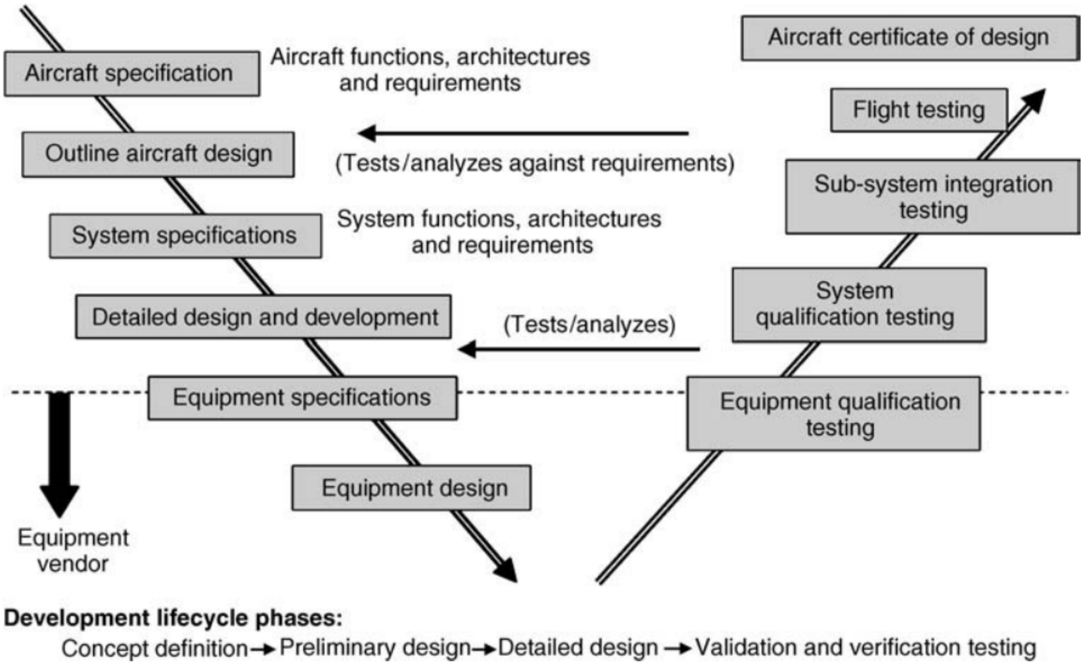


Figure 2-25 Tests in the system development 'V' model (Drysdale, 2010)

2.5 Approaches for assembly sequence generation

The activity of designing an assembly process is called process planning, and the determination of the assembly task is assembly sequence planning (ASP) (Marian, 2003). These processes consist of specific sequencing or precedence requirements in that assembly tasks must precede other tasks (New, 1977). 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. As discussed in the introduction chapter, there are two roles of assembly process planning. The roles reflect to two aspects of planning concerns in ASP, which are design characteristics and manufacturing operations (Scallan, 2003). The assembly sequence generation methods are investigated into the two aspects respectively. Besides, previous investigations indicate that the aircraft assembly sequence has many constraints from the functional interactions as well as physical aspect for advanced aircraft system. It is very interesting to investigate the SE principles that support assembly integration sequence.

2.5.1 Methods based on product characteristics

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 researches (Jones, Wilson and Caton, 1998; Marian, 2003; Sebaaly and Fujimoto, 1996). 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 (Marian, 2003; Rashid, Hutabarat and Tiwari, 2012). For example, assembly precedence and geometrical constraints are normally considered to be absolutely constraints. Assembly tool, assembly stability, and assembly direction choosing are classified as optimization constraints. 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 specialised assembly criteria (Jones, Wilson and Caton, 1998; Jones and Wilson, 1996; Sebaaly and Fujimoto, 1996). By contrast, the optimization constraints include assembly tool, assembly path, and stability constraints (Rashid, Hutabarat and Tiwari, 2012). At early conceptual design stage, as many of the information needed for optimization constraints are 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 (Jones, Wilson and Caton, 1998; Jones and Wilson, 1996). However, these basic concepts are still working on the manual work of assembly process planning for complex product, which is normally considered as the field of assembly experts (Ríos, Mas and Menéndez, 2012b; Wang, 1997). In implementation of absolute constraints, the physical connection information is used widely to support assembly sequence generation in ship outfitting and aircraft structure assembly (Caggiano, Marzano and Teti, 2016; Ríos, Mas and Menéndez, 2012b; Wei, 2012a). The liaison diagram method can be applied for manual and automatic generation of assembly precedence through physical connections (De Fazio and Whitney, 1987; Wei, 2012b). 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” (Ben-Arieh and Kramer, 1994), “AND/OR graph” (Homem de Mello and Sanderson, 1991) , graph-theoretic assembly decomposition method (Ko et al., 2013), and the CAD integrated “assembly tiers” method (Pintzos et al., 2016), which both strongly rely on physical contact information. 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 case.

The Design for Assembly (DFA) method from the product design field has also been investigated. The DFA method focuses more on ease of assembly through simplifying the product design and operation optimization from human factors (Lockett, Fletcher and Luquet, 2014; Marian, 2003; Robert et al., 2012). Assembly precedence problems in DFA are mostly the so-called “assembly in the small” mechanical issues like the airframe assembly issues, rather than the “assembly in the large” sequence issues like the sequence precedence with other functional components (Jefferson et al., 2015; Whitney, 2004).

2.5.2 Methods towards manufacturing operations

As many researches of assembly line design assume that “there is a competently designed assembly ready to be assembled” (Whitney, 2004), they concentrate on the throughput predicting, line balancing, supply chain and operation cost. The assembly sequence is the basis for operations improvement and optimization. In this field, the typical design tasks are analysis of the assembly sequences and splitting large work orders into shorter work steps, and then putting them in a Gantt chart or network plan for integrating and representing technological interdependencies and spatial constraints (Frankenberger, 2007; New, 1977). The methods used for these tasks are assembly line balancing (ALB) and lean manufacturing principles. It is noticed that many of the ALB researches are about sequence generating algorithm optimization (Rashid, Hutabarat and Tiwari, 2012; Rekiek and Delchambre, 2006). In addition, lean manufacturing are actually a set of general guidelines and manufacturing strategies including Just in Time (JIT), takt time, one-piece flow, standard working and continual improvement, which are used to support the ALB (Baudin, 2002; Jones and Hazlehurst, 2003; Li, 2013). It is also acknowledged that these methods are not fully suitable for aircraft final assembly line (FAL) design, because the aircraft final assembly process relates more to the technological criteria than to manufacturing operation parameters (Ríos, Mas and Menéndez, 2012b). At conceptual design stage of an assembly line, these methods are even not available since workload smoothing is addressed based on existing production data after the FAL configuration and work content defined are finished.

2.5.3 SE concept to support assembly integration sequence

It is already known from previous investigations that the system installations and tests are arranged in certain sequence in an assembly process. The problem of system assembly sequence planning can be recognised 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 (Society of Automotive Engineers, 2010). This is one limitation in current SE practice. Research on SE implementations in manufacturing are mostly about manufacturing management and production system design (Milner, Volas and Sanders, 2013; Sage, 1996; Verbeek, 2013). Altfeld emphasizes in his book that “analyses of assembly and integration processes may well change the original layout of the product architecture” (Altfeld, 2010), 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 2-25, 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 (Guenov et al., 2016), which is called the RFLP (Requirements engineering, Functional design, Logical design and Physical design) SE framework (Gausemeier and Moehringer, 2003; Vasić and Lazarević, 2008). 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 (Baughey, 2011; Kleiner and Kramer, 2013). 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. However, Baughey and other researchers does not apply the RFLP approach to assembly line planning. Dassault Systèmes implemented the RFLP modelling approach in the PLM software CATIA V6, which provides a software framework that can be used to implement RFLP model linking product requirements to functional models, logical models and finally 3D assembly models (see figure 2-26).

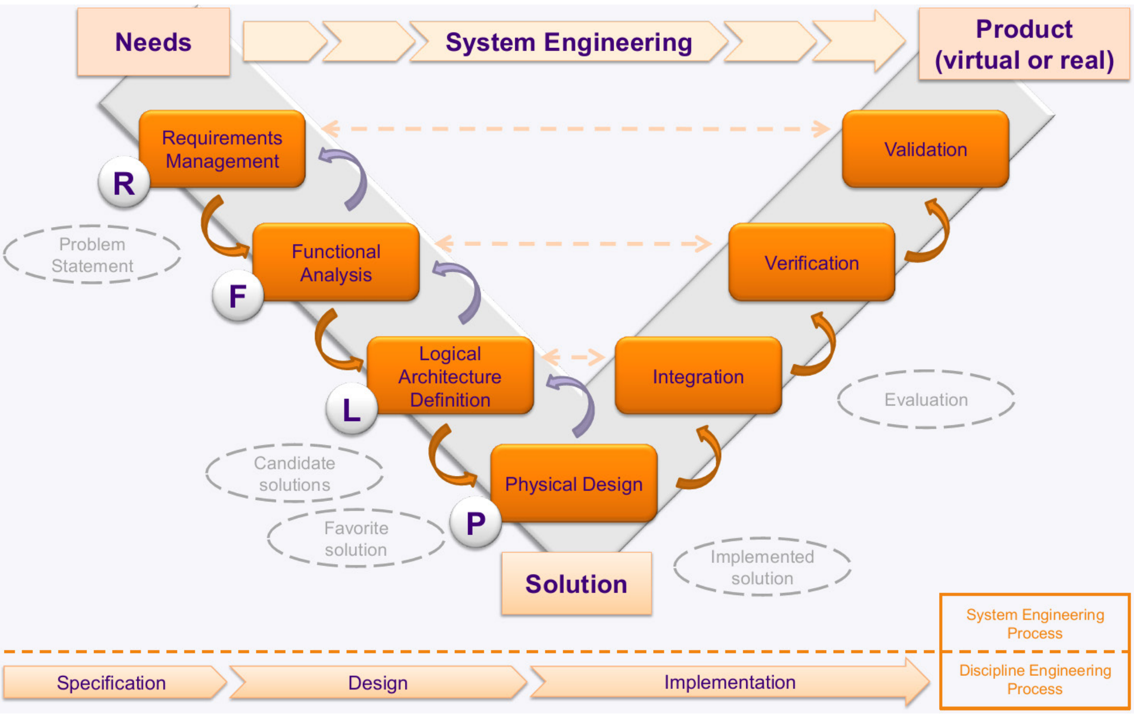


Figure 2-26 Dassault Systèmes RFLP implementation process (Dassault Systèmes, 2011)

The RFLP representation provides structured links between requirements and system function as well as physical assembly information which are not easily accessible in traditional aircraft engineering data sources that release 2D drawings, 3D assembly models and system test documents separately (Li and Lockett, 2017). The RFLP approach is mostly used to allow for better data integration and system behaviour simulation during the design process. In this research, since it connects design requirements and 3D physical models, it may provide an opportunity to support generating the installation and test sequence at an early assembly line design stage.

2.6 Product life-cycle management system

A product life-cycle management (PLM) system controls, manages and shares product related information to achieve company's business aims (Saaksvuori, 2005). It is well known as an important part of the digital manufacturing approach. A PLM system deals with the creation, modification, and exchange of product information throughout different stages of the product life-cycle (Boschian, Fanti and Ukovich, 2012). However, in 1990s' the initial concept of

PLM was introduced to meet the needs of controlling and managing the design data from CAD tools. At this time, PLM was referred to as Engineering Data Management and then Product Data Management (Mas et al., 2015; Saaksvuori, 2005). Traditionally features of PLM systems are not developed for implemented in manufacturing stage until the middle of 2000s' (Mas et al., 2015). After that, the development of PLM system changed to integrate more product related information including requirement engineering, production, maintenance, and customer service. This change follows the growing implementations of digital manufacturing philosophy. As engineering data sources can be accessed directly in the PLM system by manufacturing department, it helps to manage engineering changes on manufacturing activities. The further benefits include improved cost, product quality and requirements consistency, especially for high complex product in aerospace industry (Messaadia et al., 2012). By applying the Software-as-a-Service (SaaS) concept, the recent cloud-based PLM system provides its features in lightweight clients for all the stakeholders in product life-cycle, which achieves better product information integration, sharing and reusing (Mishra et al., 2017). Such a PLM system meets the needs of flexible and distributed manufacturing. Most of the current PLM system packages provide very similar features to support running a digital factory business process. This research focuses on the integrated design and manufacturing processes from the aspect of aircraft system assembly integration. To help finding the research gap in the implementation environment, it is helpful to have a brief comparison between digital design and manufacturing tools investigated before. This includes the traditional CAD tool, MBSE tool, and PLM system. These tools are the mostly used ones in current aerospace industry (see Table 2-3).

Table 2-3 A comparison of implementation tools used in aerospace industry (concluded by the time of thesis writing based on information from (Deuter and Rizzo, 2016; Hull, Jackson and Dick, 2013; Madni and Purohit, 2019; PAT Research, 2018)**)**

Vendor	**Type**	**Software features**			
		Requirement modelling	**Architecting (MBSE)/functional modelling**	**Physical modelling (CAD)**	**Links between lifecycle models**
PTC Windchill	PLM	Yes	Yes, in PTC Integrity packages	No (links to CAD in Creo)	From requirements to parts in design
Siemens Teamcenter	PLM	Yes	Yes, in a separated MBSE module	No (links to CAD in NX)	From requirements to parts in design
Dassault Enovia	PLM	Yes	Yes, in CATIA V6/ 3D Experience MBSE packages	No (links to CAD in CATIA)	Between different requirements in PLM From requirements to parts in design
Dassault CATIA V5	CAD	N/A	No	Yes	No
Dassault CATIA V6	CAD	Importing data only	Yes, in RFLP module	Yes	Define traceability links between RFLP
IBM Rational	MBSE	Yes, in DOORS package	Yes	No	From requirements to parts in design
No Magic Cameo Systems Modeler	MBSE	Yes	Yes	No	From requirements to parts in design

The comparison results show that today's PLM systems are more integrated with traditional MBSE and requirement engineering features, ensuring the requirement traceability and consistency. It is also found the CATIA V6 tool has a specialized SE RFLP module that support design and modify the product architecting and CAD models in a unified platform. At the design tool side, CATIA V6 is easy to access the requirement and product architecting information from ENOVIA PLM system. Thus, CATIA V6 is considered to be an ideal implementation environment for this research.

2.7 Research Gaps

In modern advanced aircraft, the systems are complex both in physical and functional integration. Currently, there are no methods and approaches to directly support the generation of detailed assembly integration sequences of complex aircraft systems for assembly process planning. Most previous research considers only the physical connections when defining the initial feasible assembly sequence and ignores the functional interactions (Caggiano, Marzano and Teti, 2016; Ko et al., 2013; Ríos, Mas and Menéndez, 2012b; Wei, 2012a). None of them use product functional information for assembly sequence generation. 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. It is also recognised 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 product engineering data source, the verification tests in the assembly line may not have the proper test scope or may fail to be arranged at the right time.

2.8 Chapter summary

This chapter investigates the general aircraft system development process, and the characteristics of modern advanced aircraft systems, as well as their influence on assembly process planning. The existing assembly sequence generation methods are also investigated and found current methods are mostly based on the physical connection information. Some projects mentioned the system integration work in an assembly line, but in generating the assembly sequence, they seldom consider the constraints from the functional aspect. As the literature indicates the system integration process should follow the SE verification principles, ignoring the functional constraints will cause potential development risk at later flight test and aircraft in-service stage.

According to literature, DSM has the advantage of defining and managing the interactions between systems, and QFD captures requirement and deploys them to production line control plans. Although the two tools cannot directly support assembly sequence generation, they are still valuable for interactions definition and management at design stage. They will be tested in simple examples to find whether they are suitable to support the integration of physical and functional engineering data sources, and whether the deployment process can be used in requirement decomposition from such data sources.

The RFLP framework provides a software environment that can model the requirements decomposition process, which finally associates requirements with the 3D physical design data. It also has the potential to extract associated functional information to support generating the detailed installation and test sequences.

The next chapter will introduce the overall research methodology, and explain the project validation method.

3 RESEARCH METHODOLOGY

This chapter presents and explains the research methodology that was followed in this research. The general research process is shown in a flow chart, and the validation methodology is discussed in details.

3.1 Thesis research methodology

According to the Giachetti (2016) , SE research methods can be experimental, design, empirical study, analysis methods, or a combination of these methods. A brief comparison of these methods is shown in table 3-1.

Table 3-1 A comparison of SE research methods (concluded based on information from (Giachetti, 2016))

Method	Research activities	Example
Experimental	Examine a hypothesis by experiments	UAV control and performance tests
Design	Design a system or software tool and document success or failure of the prototypes developed and built to test the design ideas	Aircraft fuel system design
Empirical	Examine a research question or hypothesis by survey/interview data collections	Interviews about humans performing the engineering
Analysis	Examine a research question by using quantitative or computational analysis.	Feasibility of a product design

The aim of this research is to develop a method and tool for aircraft assembly sequence generating from design data. Thus, primarily this research can be defined as design research. Besides, as the research question in section 1.2 asks whether SE principles can be used to support assembly planning, it is also analysis research. Finally, the validation of the developed assembly planning method is empirical research. Based on these reasons, it is decided to apply a combination of the three methods mentioned above.

3.2 Research activities

This research concentrates on the aircraft assembly integration, which brings aircraft design and assembly planning together. A combination of different research methods means they are applied at different research stages. The main research activities include literature review for analysis, design and modelling for the method development, case study and empirical research for validation. The methodology is shown in figure 3-1.

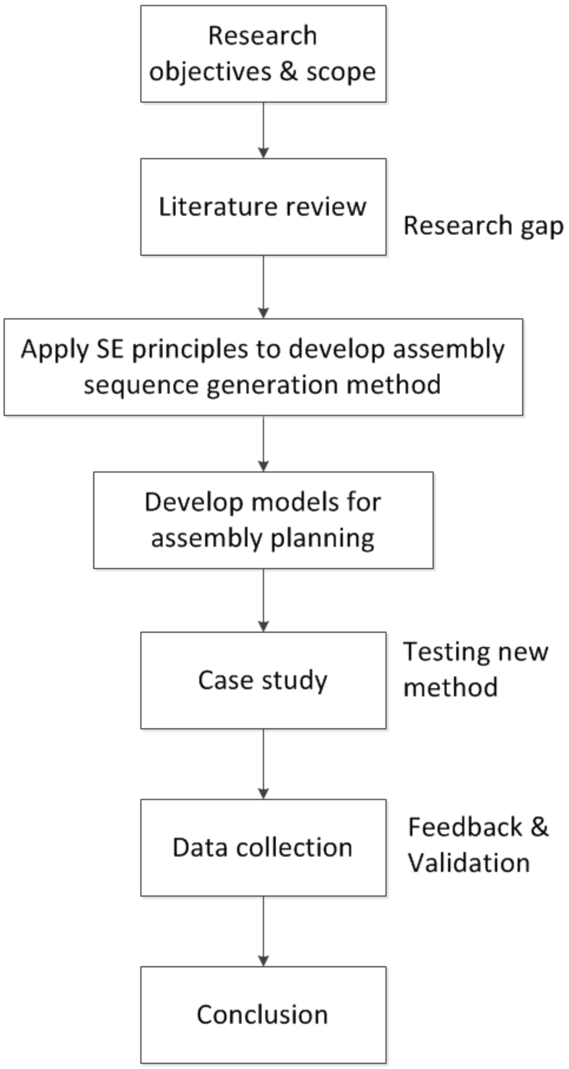


Figure 3-1 Research methodology flow chart

3.2.1 Apply SE principles to develop new method

To answer the hypothesis "could SE principles help assembly planners to better understand product design data and thus support generating more reliable installation and test processes for assembly line design ?", it is decided to design a tool, then test its feasibility in case study. The design method aims to describe the system development process and problems within the process (Giachetti, 2016). The method will help to build a 'V' diagram mapping those development activities and related engineering inputs and outputs. Once the development process goes to assembly planning stage, the analysis method is used to help making sequencing decisions. It would be a set of assembly analysis questions in a flow chart, such as consistency, accessibility and operational questions.

3.2.2 Develop models for assembly planning

One of the research gaps found in literature review is that aircraft system functional design information is not well integrated with physical 3D models. This brings further difficulty for assembly planning in manufacturing engineering. The SE modelling method is selected for this research stage to try to create aircraft functional models in terms of system functionalities, architecting and sub-system interactions information. Traceability links are also created in the modelling process, which will make the requirements, functional and physical models more integrated. As a result of that, assembly planning would access the dependencies directly from the modelling results in model reuse. The tools supporting system dependencies modelling will be considered as candidate methods, and then tested with simple examples. Based on the lessons learnt from the candidate methods from literature review, this research can decide a baseline for the proposed new method.

3.2.3 Case study

This research has a strong background of current aircraft system design and manufacturing process. Due to the complexity of advanced aircraft systems, it is decided to create two detailed case study models that will allow the developed method to be tested. The two case studies have different emphases in testing the proposed method. The first case study is based on the nose bay of a business jet with integrated system architecture. The main purpose of selecting this case study is to study and understand the general RFLP modelling process and technique to develop the modelling rules thus ensuring the model reuse in the assembly deployment. The first case study therefore only has simplified design information including:

- Simplified system design requirements that only contain the required structural nodes of three major systems.
- Simplified system 3D CAD models from three major systems that only represent the general assembly layout and connections information between systems and nose bay structure.
- Minimised dependencies between system components and structural assembly (i.e., the bay is open access for system equipment).

The second case study is a more complicated one which is partly based on a representation of Boeing 777 aircraft design information and EASA (European Union Aviation Safety Agency) CS-25 requirements. The fuel system, electrical power system and environment control system (ECS) in the wing section are used to test the proposed method. It contains more detailed requirements, more structure and systems 3D CAD models, which allows more analysis to be done with assembly constraints.

3.2.4 Data collection

This research aims to help assembly planning engineers to better generate assembly sequence from aircraft complex systems. It is not possible to validate the method through the industrial application within the time or budget of the PhD study. Therefore, project feedback from people with industry background especially the ones who have both design and manufacturing knowledge are crucial for the research results validation. As feedback data are in the form of transcribed textual documents from interviews, the qualitative data analysis method is introduced in data collection. Miles and Huberman (1994) state in their book that qualitative data analysis method is the best strategy for explore a new area and develop hypotheses. In this method, the semi-structured interview is a balance between flexible open-ended interview and structured survey (Miles and Huberman, 1994). Following on the guide of semi-structure interview, the interview strategies are:

- Develop a set of questions related to this research. Use open-ended questions like “what do you think about the definition of aircraft complex systems”, and avoid two-in-one questions.
- Select participants carefully. They should be an aircraft system or structure designer with assembly line working experience, assembly engineer who understands system design well, people in academia with strong design or manufacturing background, and SE engineers working in industry.
- Use colour coding to pick up common ideas and statements, and then group them as topics to help data analysis. Validation conclusion can be made based on these topics with future work to be done.

3.3 Chapter summary

This chapter introduces of research methodology used for this research. A combination of research methods are selected for the overall research process. It also explains why semi-structured interview method is selected as methodology in data collection and research validation. The next chapter will investigate and test current tools that support dependency information modelling first. Then, it will try to combine the advantages of current tools and software environment to propose a new approach for aircraft system assembly integration sequence generation.

4 ASSEMBLY GENERATION METHOD DEVELOPMENT

This chapter describes the new method development. The two existing tools DSM and QFD are tested first to allow lessons learnt from them. Then, the development strategy changes to apply SE principles for method development. Based on the analysis of assembly integration activities in SE view, detailed needs for a new assembly sequence generation method can be specified. New proposed method is finally developed based on these needs.

4.1 Tests on DSM and QFD

4.1.1 Testing the interaction definition of DSM

DSM was identified in the literature review as a possible tool to model interactions in aircraft system design. This brief test is based on the aircraft systems design information from Moir and Seabridge's book (Moir and Seabridge, 2008), using a generic concept of two major systems under federated system architecture. Airframe structure is also included in this brief test. According to Otto and Wood (2001), the product interactions can be classified as four catalogues: spatial, energy, information and materials. The system architecture and dependencies are first finished in a simplified 2D UML diagram (see figure 4-1). Interaction links are created in the UML diagram as well. After that, a set of DSM matrices are produced from the UML diagram in Cambridge Advanced Modeller (CAM) tool (software available at https://www-edc.eng.cam.ac.uk/cam/), which is a piece of specialised software used to create DSM (Wynn et al., 2010). In figure 4-1, the physical interaction refers to spatial and materials, while functional interaction refers to energy and information.

The interactions between systems and sub-systems are presented in the matrix of matrices (MoM) using the CAM tool as shown in figure 4-2. The items with numbers indicate that the rows and columns have dependency relationship.

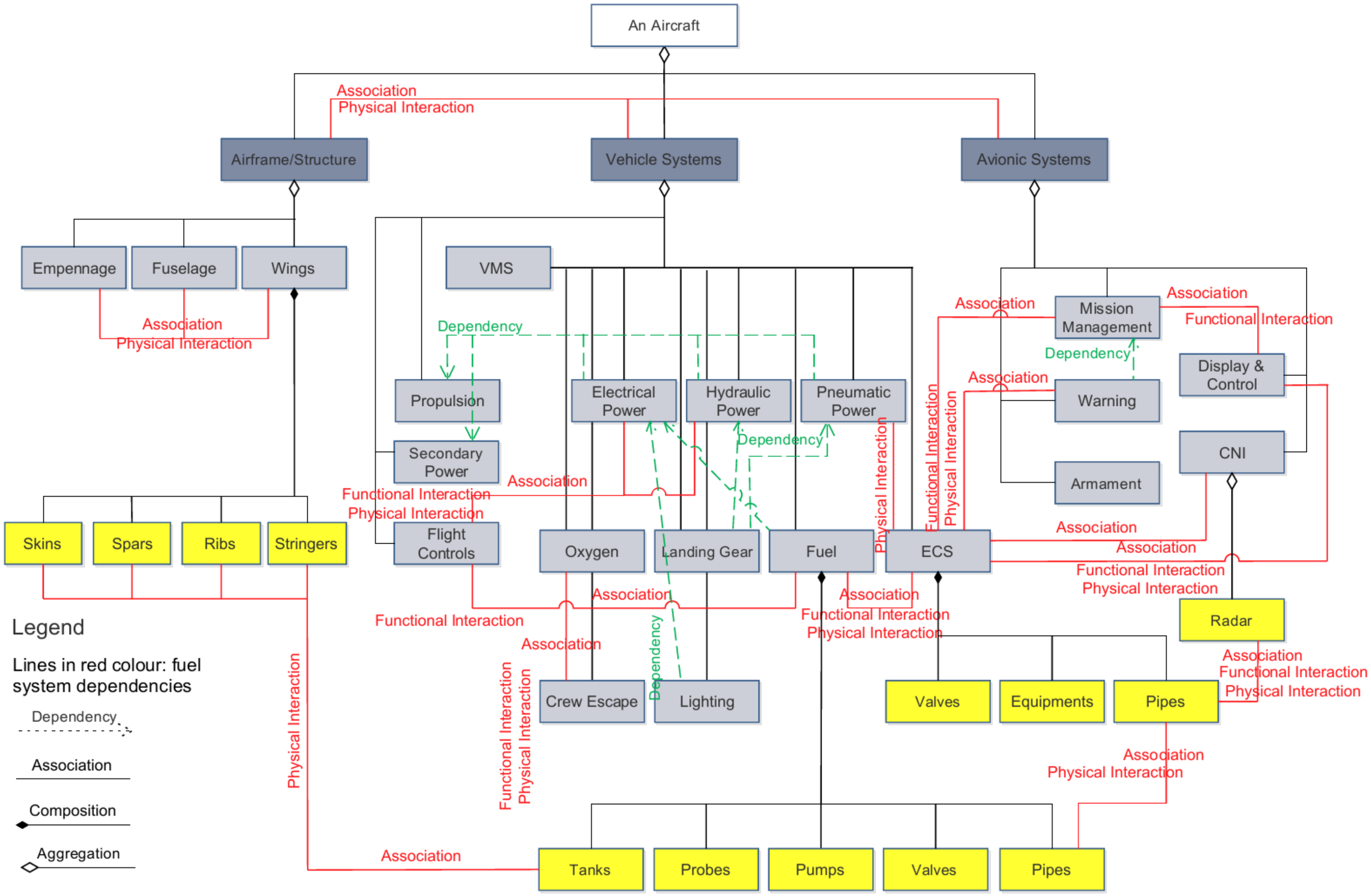
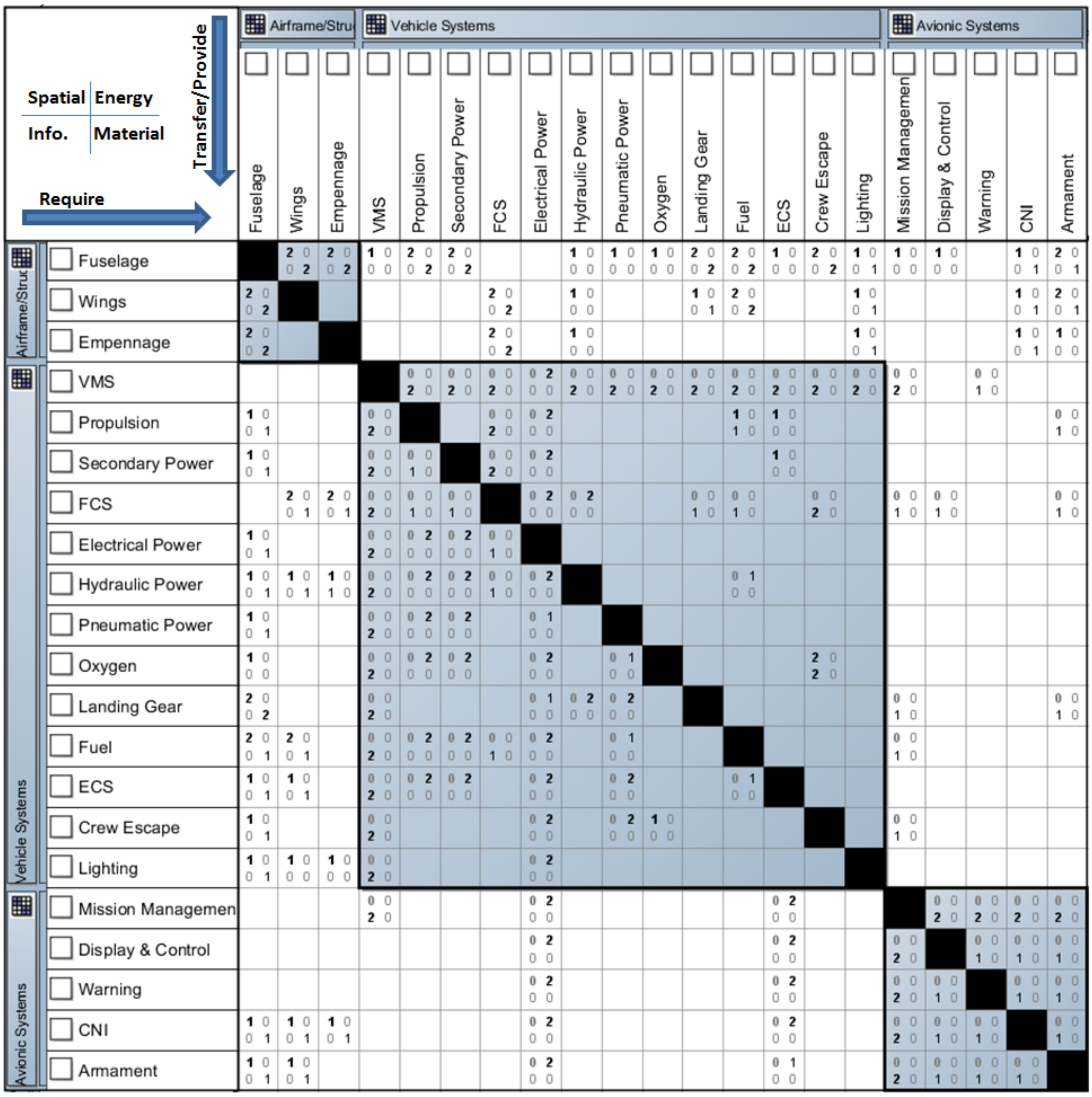


Figure 4-1 Generic aircraft system architecture and interactions definitions in the DSM matrix (by the author)

According to Wynn et al., (2010) and Wynn and Clarkson (2009), these different numbers represent the level of dependency between items in the DSM matrix: an integer numbers from positive two to negative two, which stand for required (+2), desired (+1), indifferent (0), undesired (-1) and detrimental (-2) respectively. For example, the numbers between oxygen sub-system and crew escape sub-system indicate that oxygen system strongly requires the spatial and information interactions from crew escape system. However, the rating depends on the design specifications and too much of designer's knowledge.



Spatial	Energy
Info.	Material

Transfer/Provide

Require

		Airframe/Stru			Vehicle Systems													Avionic Systems				
		☐ Fuselage	☐ Wings	☐ Empennage	☐ VMS	☐ Propulsion	☐ Secondary Power	☐ FCS	☐ Electrical Power	☐ Hydraulic Power	☐ Pneumatic Power	☐ Oxygen	☐ Landing Gear	☐ Fuel	☐ ECS	☐ Crew Escape	☐ Lighting	☐ Mission Managemen	☐ Display & Control	☐ Warning	☐ CNI	☐ Armament
Airframe/Struc	☐ Fuselage	■	2 0 0 2	2 0 0 2	1 0 0 0	2 0 0 2	2 0 0 2			1 0 0 0	1 0 0 0	1 0 0 0	2 0 0 2	2 0 0 2	1 0 0 0	2 0 0 2	1 0 0 1	1 0 0 0	1 0 0 0		1 0 0 1	2 0 0 1
	☐ Wings	2 0 0 2	■					2 0 0 2		1 0 0 0			1 0 0 1	2 0 0 2			1 0 0 1				1 0 0 1	2 0 0 1
	☐ Empennage	2 0 0 2		■				2 0 0 2		1 0 0 0							1 0 0 1				1 0 0 1	1 0 0 0
Vehicle Systems	☐ VMS				■	0 0 2 0	0 0 2 0	0 0 2 0	0 2 0 0	0 0 2 0	0 0 2 0	0 0 2 0	0 0 2 0	0 0 2 0	0 0 2 0	0 0 2 0	0 0 2 0	0 0 2 0		0 0 1 0		
	☐ Propulsion	1 0 0 1			0 0 2 0	■		0 0 2 0	0 2 0 0					1 0 1 0	1 0 0 0							0 0 1 0
	☐ Secondary Power	1 0 0 1			0 0 2 0	0 0 1 0	■	0 0 2 0	0 2 0 0						1 0 0 0							
	☐ FCS		2 0 0 1	2 0 0 1	0 0 2 0	0 0 1 0	0 0 1 0	■	0 2 0 0	0 2 0 0			0 0 1 0	0 0 1 0		0 0 2 0		0 0 1 0	0 0 1 0			0 0 1 0
	☐ Electrical Power	1 0 0 1			0 0 2 0	0 2 0 0	0 2 0 0	0 0 1 0	■													
	☐ Hydraulic Power	1 0 0 1	1 0 0 1	1 0 1 0	0 0 2 0	0 2 0 0	0 2 0 0	0 0 1 0	0 2 0 0	■				0 1 0 0								
	☐ Pneumatic Power	1 0 0 1			0 0 2 0	0 2 0 0	0 2 0 0		0 1 0 0		■											
	☐ Oxygen	1 0 0 0			0 0 2 0	0 2 0 0	0 2 0 0		0 2 0 0		0 1 0 0	■				2 0 2 0						
	☐ Landing Gear	2 0 0 2			0 0 2 0				0 1 0 0	0 2 0 0	0 2 0 0		■					0 0 1 0				0 0 1 0
	☐ Fuel	2 0 0 1	2 0 0 1		0 0 2 0	0 2 0 0	0 2 0 0	0 0 1 0	0 2 0 0		0 1 0 0			■				0 0 1 0				
	☐ ECS	1 0 0 1	1 0 0 1		0 0 2 0	0 2 0 0	0 2 0 0		0 2 0 0		0 2 0 0			0 1 0 0	■							
	☐ Crew Escape	1 0 0 1			0 0 2 0				0 2 0 0		0 2 0 0	1 0 0 0				■		0 0 1 0				
	☐ Lighting	1 0 0 1	1 0 0 0	1 0 0 0	0 0 2 0				0 2 0 0								■					
Avionic Systems	☐ Mission Managemen				0 0 2 0				0 2 0 0						0 2 0 0			■	0 0 2 0	0 0 2 0	0 0 2 0	0 0 2 0
	☐ Display & Control								0 2 0 0						0 2 0 0			0 0 2 0	■	0 0 1 0	0 0 1 0	0 0 1 0
	☐ Warning								0 2 0 0						0 2 0 0			0 0 2 0	0 0 1 0	■	0 0 1 0	0 0 1 0
	☐ CNI	1 0 0 1	1 0 0 1	1 0 0 1					0 2 0 0						0 2 0 0			0 0 2 0	0 0 1 0	0 0 1 0	■	0 0 1 0
	☐ Armament	1 0 0 1	1 0 0 1						0 2 0 0						0 1 0 0			0 0 2 0	0 0 1 0	0 0 1 0	0 0 1 0	■

Figure 4-2 Example of sub-systems interactions in DSM (produced by the author based on generic design information)

This test aims to examine the possibility of using DSM data as engineering data source that support assembly sequence generation. The DSM data is switched to a 2D network view as shown in figure 4-3 to illustrate the complexity of interactions between aircraft complex systems. The network view of dependencies shows the highly complex interactions between sub-systems even though this example is only built on a common sense of system design with federated system architecture and limited major structural sections. What is more, the interactions are defined only between sub-systems level, the system component level is not defined in this example.

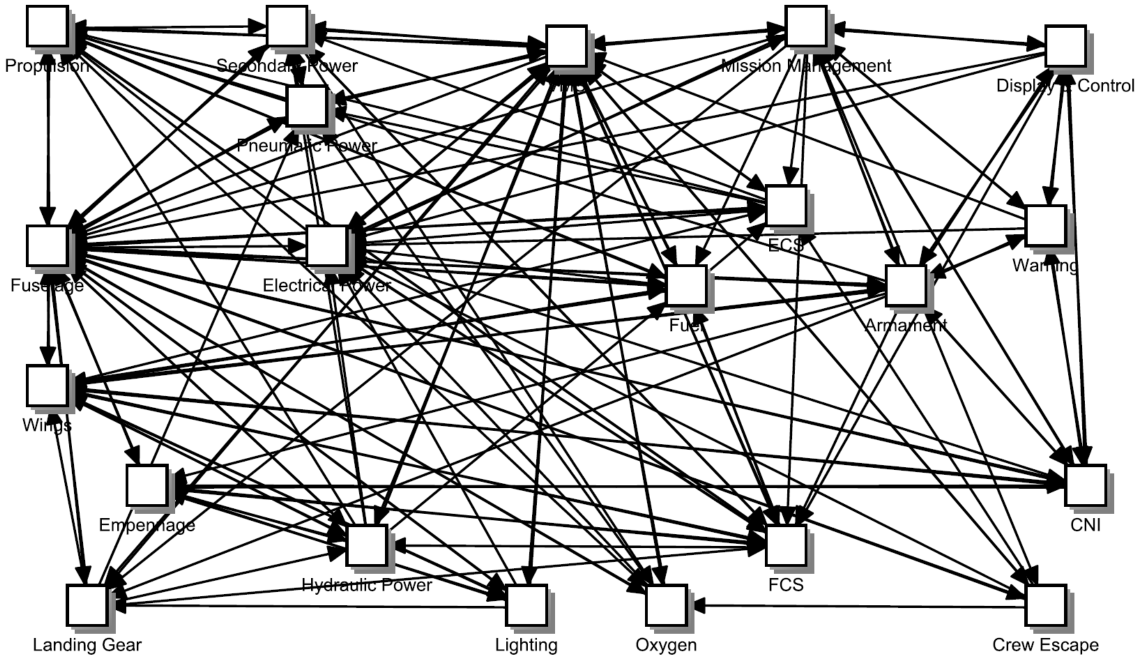


Figure 4-3 Example of aircraft sub-systems interactions complexities (Li and Lockett, 2017)

This brief test reveals that DSM is available to define interactions of complex systems, but it has several drawbacks which are not suitable to be the functional data source for the following reasons:

- It is too complicated and time-consuming to define the interactions of complex systems in the matrix of matrices.
- The large number of interactions results in a huge DSM matrix data thus not easy to read and reuse, as well as manage design changes.

- The DSM data do not link and associate to the physical data source directly.
- In practice, DSM is mostly used as a design-analysis tool

4.1.2 Testing the deployment process of QFD

QFD was identified in the literature review as a tool that support requirement deploying to production control plans. This brief test aims to test the possibility of using QFD to deploy requirements to a reliable aircraft assembly plan. Based on the principle of matrix of matrices thirty-matrix approach from GOAL/QPC organisation (ReVelle, Moran and Cox, 1998), the original “part deployment” in phase 2 of the four-phase QFD is adapted to “function allocation” for this application, and the process planning deployment matrix in phase 3 is expanded to three detailed QFD matrices. The expanded QFD approach for this test is shown in figure 4-4.

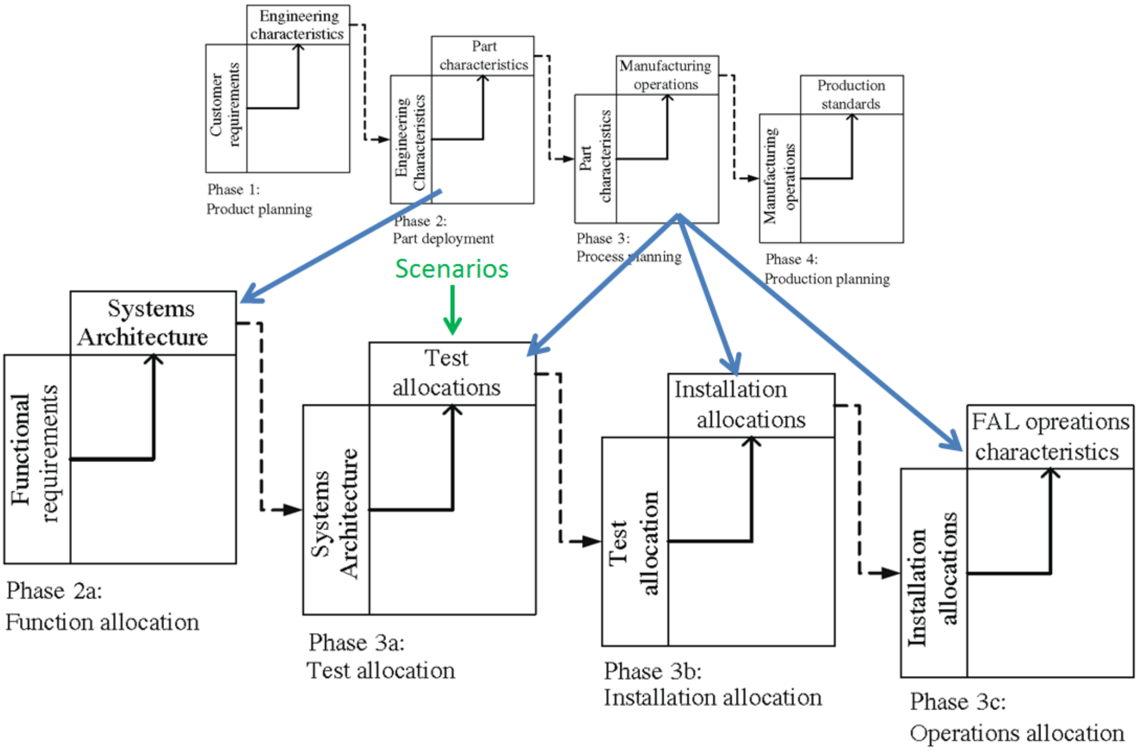


Figure 4-4 QFD approach for aircraft system assembly process planning (Phase 1 to 4 from (ReVelle, Moran and Cox, 1998)**, adapted phases by the author)**

This test then uses the design of a wing section fuel system within the vehicle management system architecture as an example to find whether the fuel system installation sequence can be generated from the deployment process. The example covers the phases from phase 2a to phase 3c in figure 4-4. The fuel functions used in this example include fuel storage, fuel transfer, engine feed, refuel/defuel, quantity measurement, heat exchange, system cleanliness and CG (Centre of Gravity) control. It is assumed these functions are the results deployed from customer requirements in phase 1 “product planning”. At each phase, the dependency relationship is decided by rating numbers for priority index level in the QFD diagram. The pre-defined priority numbers are: 9 for “strong”, 3 for “moderate”, and 1 for “slight or possible”.

Rate for the relationship

Strong - 9
Moderate - 3
Slight or Possible - 1

Assuming all tanks have these parts
Assuming all valves are electrical controlled

	Installation Allocations	Assembly Stage	Pre-assembly		Sub-assembly																	Final assembly																		Ground operations						
		Installation Activites	Pre-fit parts	Equip. packs	Wing stucture assembly	Wing structure sealing	Fuel transfer pipes in tank ins.	Fuel transfer valves in tank ins.	Fuel transfer pumps in tank ins.	Engine feeding pipes in tank ins.	Engine feeding valves in tank ins.	Engine feeding pumps in tank ins.	Pressurisation & Vent pipes in tank ins.	Pressurisation & Vent valves in tank ins.	Refuel/Defuel pipes in tank ins.	Refuel/Defuel valves in tank ins.	Fuel wiring in tank ins.	Quantity probes ins.	Fuel level sensors ins.	Wiring pipes ins.	FOD work	Wing and fuselage mate	Fuel transfer pipes mate	Fuel feeding pipes mate	Pressurisation & Vent pipes mate	Refuel/Defuel pipes mate	Electrical mate	Engine feeding pipes connection & ins.	Engine feeding valves connection & ins.	Engine feeding pumps outside tank ins.	Engine feeding filter ins.	Pressurisation pipes outside tank ins.	Pressurisation valves outside tank ins.	Pressurisation air filter ins.	Refuel/Defuel pipes outside tank ins.	Refuel/Defuel valves outside tank ins.	Refuel/Defuel filter ins.	Cable harness ins. and connection	FOD work	Engine feeding pipes connection	Electrical Cable plugs connection	Engine feeding filter work	Pressurisation air filter work	Refuel/Defuel filter work	FOD work	
Test Allocations	Airtightness test	Fuel transfer sub-system in tank airtightness test	3				9	9													3																								24
		Engine feed sub-system in tank airtightness test	3							9	9										3																								24
		Pressurisation & Vent sub-system in tank airtightness test	3										9	9							3																								24
		Refuel/Defuel sub-system in tank airtightness test	3												9	9					3																								24
		Measurement sub-system in tank airtightness test															3			9	3																								15
		Center wing tank and overall sub-systems airtightness test				9	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9																								60
		Right wing tank and overall sub-systems airtightness test				9	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9																								60
		Left wing tank and overall sub-systems airtightness test				9	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9																								60
		Overall system airtightness test after mate and enginee ins.																				9	9	9	9	9	3	9	9		9	9	9	9	9	9	9		3	9					3	144
	Wiring connection test	Center tank wiring connection test		3													9				3	3					9											9	3							39
		Right wing tank wiring connection test		3													9				3	3					9											9	3							39
		Left wing tank wiring connection test		3													9				3	3					9											9	3							39
		Fuel system lower Unit interface connection test																									9		9	9			9			9		9	3							57
	Power-on test	Included in VMS lower interface HIL test						3	9		3	9		3		3	9	3	3			1					9		3	9			3			3		9	3							85
	Functional test	Included in VMS upper interface test				1											1										9											9	1		9				1	31
		Included in VMS HIL test (fuel system)				1		9	9		9	9		9		9	3	9	9								9		9	9			9			9		9	1		9				1	141
	Operational test	Included VMS overall system test (fuel system)				1	1	3	3	1	3	3	1	3	1	3	3	3	3	1			1	1	1	1	3	1	3	3	3	1	3	3	1	3	3	3		1	9	9	9	9	9	113
			12	9	0	30	19	33	30	19	33	30	19	33	19	33	55	24	24	19	51	19	10	10	10	10	69	10	33	30	12	10	33	12	10	33	12	66	20	10	27	9	9	9	14	

Figure 4-5 Deploying tests to installations in phase 3b (by the author)

The QFD deployment results include four diagrams which show the serial process from system functions to system architecture, system architecture to test tasks, test tasks to installation tasks, and finally installation tasks to the required assembly facilities for operations. Figure 4-5 shows the installation allocation result in phase 3b (a full version of the results is provided in the Appendix A). The numbers in the diagram indicates the priority index of the test related installation task, and the sum numbers around the diagram shows the priority of the installation or test tasks. For instance, the result in figure 4-5 indicates that cable harness wiring/connection and electrical mate work are high-priority installation tasks, and the functional test and operational test are the most important tasks in the assembly process. The rating results may reflect the sequence of installation and test in some extent. However, when using the QFD deployment process to support assembly process planning, the drawback can be concluded as follows:

- In the deployment process, the test and installation tasks in the matrices are decided by experience rather than generated directly from engineering data.
- The priority index rating depends heavily on personal experience and lessons learnt before.
- The rating results do not have strong links to a feasible assembly sequence, which only can be used as reference.

4.1.3 Test summary

According to the two tests results, DSM and QFD are not suitable to support assembly integration design for complex systems. It is very challenging to define the high-level complexity system dependencies in DSM matrix, thus it is not an alternative functional engineering data source compared to the traditional 2D system schematics. QFD has the advantage of deploying requirement to production control plans through several development stages. In supporting of assembly sequence generation, QFD is found to be a design-analysis tool based on existing test and installation tasks. This is because QFD cannot generate these plans from engineering data source but rates them for priority level. Although DSM and QFD are not suitable for this project, some ideas from them would be used to develop the new method, including:

- In the new engineering data source, system interactions should associate with both functional and physical integrations, and they should allow for easy for data management.
- There should be a way to link requirements, functional design, physical model, and finally the assembly tasks in two directions.
- The initial installation and test sequence should be generated directly from the engineering data source than personal experience.

As introduced in section 2.5.3, the SE RFLP framework provides an opportunity to link requirements, functional, logical and physical information at design stage. It is also found in literature the integration of product function follow the path of assembly, and aircraft complex systems are developed under SE principles. The next step of method development will consider combining these concepts into a structured method through the following technical approach: “Requirements” to “Functional-Test” and then “Logical-Physical-Installation”.

4.2 Using SE principles for method development

The functional interdependencies of system components contribute much to the development difficulty of the overall system integration process in both design and manufacturing. In the assembly line conceptual design stage, the assembly process planning should consider both physical and functional constraints to generate a feasible process. SE principles are used here to integrate design, assembly, and RFLP framework with in the same ‘V’ model for new method development.

4.2.1 Assembly integration activities in the ‘V’ model

The overall aircraft system development ‘V’ model from Drysdale (2010) (see figure 2-25) gives a general picture that the complex systems are linked with design activities and different verification tests. If focusing more on the production verification tests in an assembly line, Drysdale’s ‘V’ model is then adapted by the author to incorporate the tests in figure 2-21 as a new ‘V’ model (see figure 4-6). The adapted 'V' model further clarifies the relationship between assembly integrations and system design activities. In the bottom-up process, the system components and equipment are first installed in sub-assemblies. The finished sub-assemblies are verified in individual sub-system tests to check for sub-system design specifications. Similarly, the main assemblies and complete system are verified for system level specifications and aircraft level requirements respectively. SE principles are now used to connect assembly integration activities within the system development 'V' model to the overall product development life-cycle. It also shows the requirements are decomposed to detailed design information that can be used to support assembly integration. This process fulfils the design and production verification. Once the technical approach is built, these items in this 'V' model are all associated. The next step is trying to build the requirement tracing mechanism to ensure the engineering data produced in this process is easy to access and extract for assembly sequence generation.

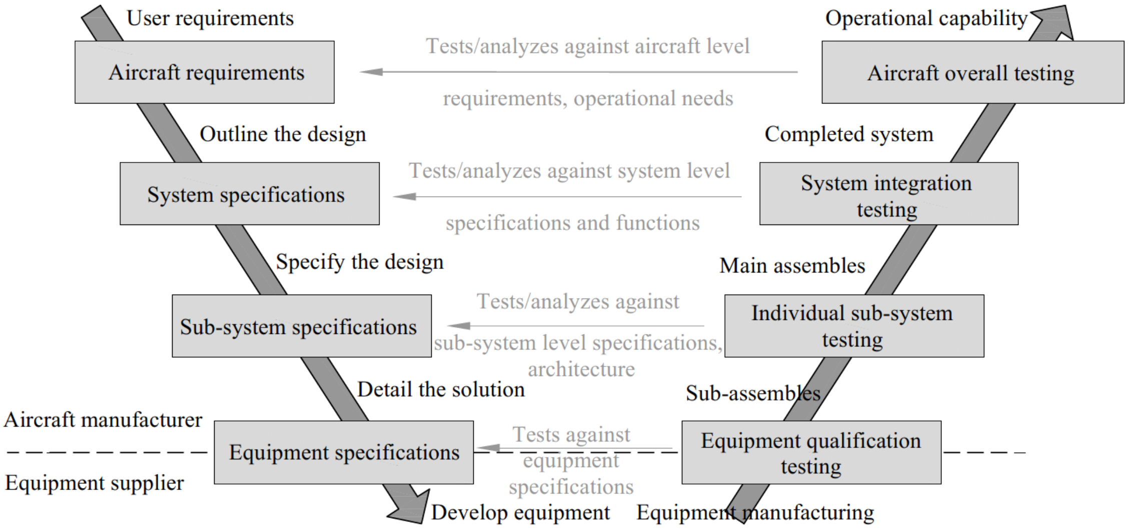


Figure 4-6 Aircraft system development 'V' model associated with assembly testing

4.2.2 Integration of design and assembly with RFLP process

In the aircraft development process, assembly line design is concurrent with aircraft product design (Mas et al., 2013). Assembly process planning is one of most important parts in assembly line design. In concurrent engineering, assembly process planning works in parallel with aircraft design (Boothroyd, Dewhurst and Knight, 2011). To have a comprehensive understanding the relationship between system design, assembly planning and their engineering outputs at each stage, a modified ‘V’ model is developed based on the ‘V’ model in figure 4-6, to clarify their relationships under the product design and assembly line design life-cycle model (see figure 4-7). It should be noticed that some activities with dashed line in figure 4-7 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. This assembly integration ‘V’ model helps in understanding the needs of engineering data outputs at design stages that support assembly sequence generation.

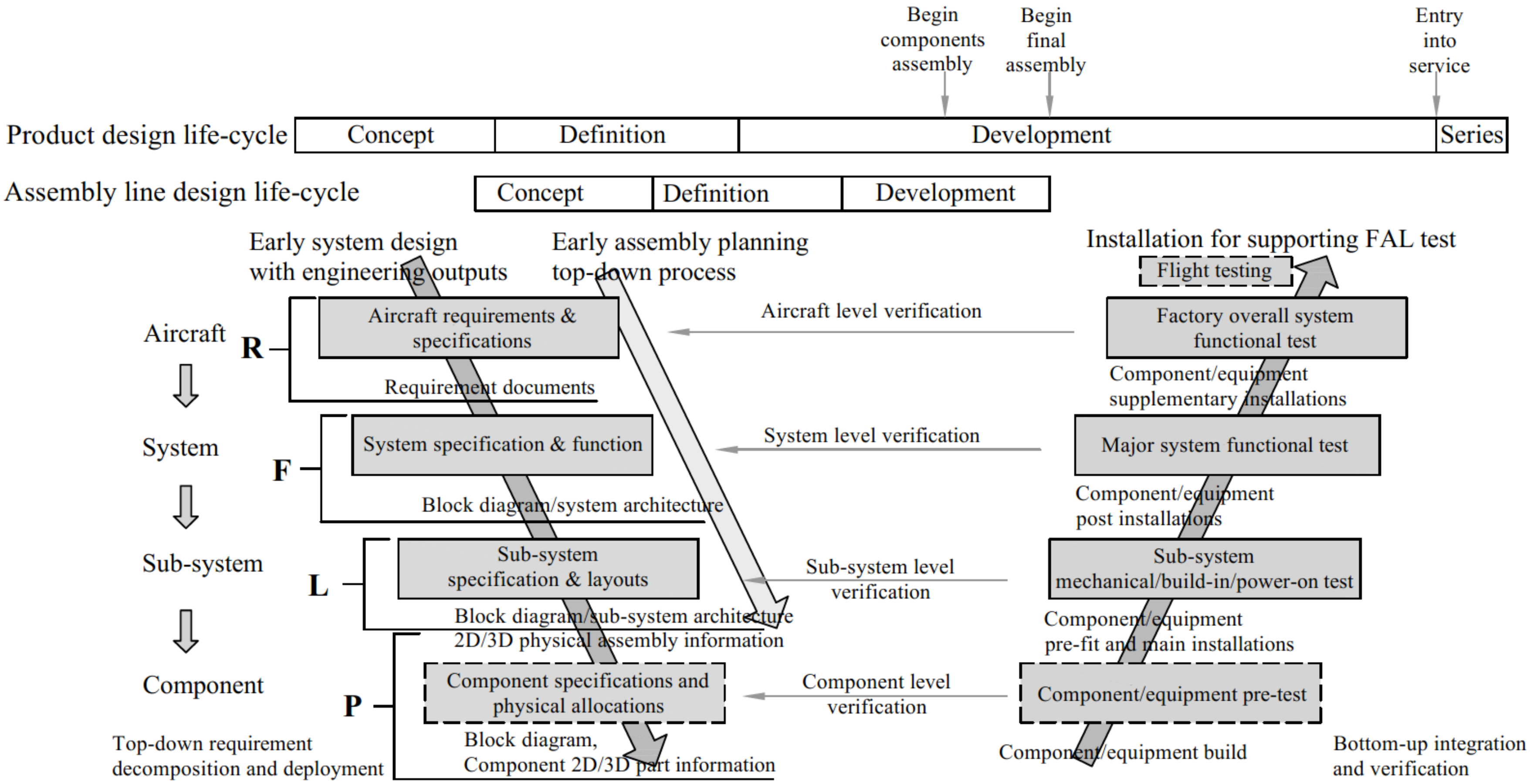


Figure 4-7 Aircraft system integration 'V' model from assembly line view (concurrent life-cycle model based on (Mas et al., 2013))

In figure 4-7, 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. The RFLP framework covers the major design stages in this top-down process. 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 (Li and Lockett, 2017). The needs of the developing 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.

(4). Assess the generated installation and test sequence.

4.3 Implementation concepts

The SE RFLP framework found in literature review is selected as the implementation framework and fundament for method development (Baughey, 2011). Based on the technical approach “Requirements” to “Functional-Test” and then “Logical-Physical-Installation” (see section 4.1.3) and the relationship presented in figure 4-7, the implementation concept of RFLP modelling that supports the assembly sequence generation is illustrate in figure 4-8.

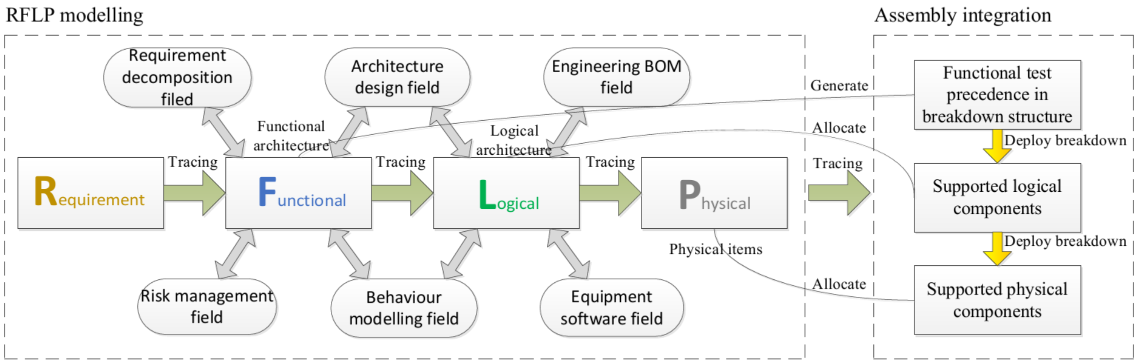


Figure 4-8 Implementation concept of RFLP modelling for assembly sequence generation (original RFLP implementations based on (Baughey, 2011)**)**

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. 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). Besides these original RFLP implementations introduced by Baughey (2011), the assembly implementation concept gives a general image of how the RFLP modelling data are treated as engineering data source to support assembly integration design.

The assembly integration sequence can be treated as a breakdown structure constrained by tests. The implementation of assembly integration sequence generation proposed in this research 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.

4.4 Proposed method framework

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 & 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 (A. Delchambre, 1996). From the SE view, the proposed approach should be applied in an iterative way to give greater benefits. In the proposed method, the integrated CAD should also connect two user roles: the aircraft system designer and assembly planner. This will help 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 experience-based approach. The method is planning to implement 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.

The proposed method in this project 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 4-9.

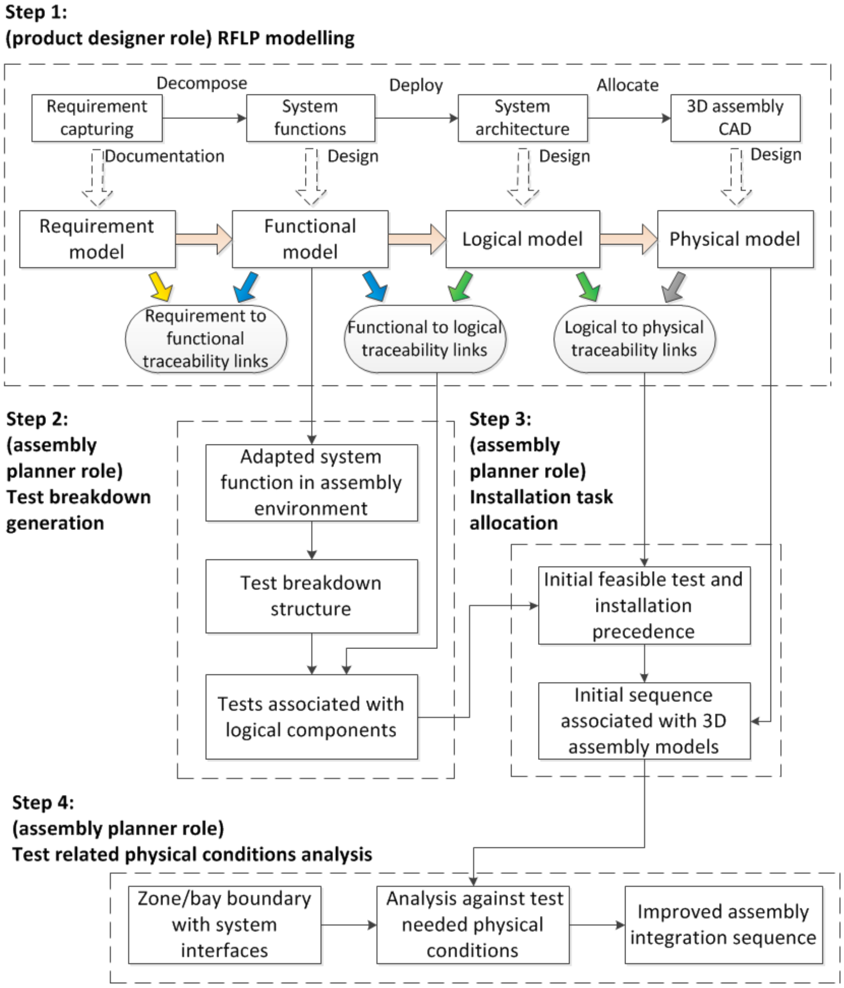


Figure 4-9 Assembly sequence generation using RFLP models

The method has four 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. Specialised 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 in the next section. These modelling rules are part of the novelty in the proposed method. 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.

Step 2 to step 4 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 the 3D physical CAD models, thus produce the initial feasible integration sequence. Step 4 is developed based on the zonal analysis idea from ZSA, which is used to analyse physical installations that are required for a specified test. It assess whether the generated initial sequence is feasible for the test related physical conditions, such as the accessibility of test facility interfaces after systems installations, and the need of systems uninstallation/installation in the test process. Such analysis and installations in step 4 are all referred to “test related physical conditions” and “test related physical installations” separately.

Detailed explanations of the method workflow are provided in the following sections.

4.5 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:

- Boundary identification rule
- Interaction definition rule
- Traceability definition rule

The modelling rules use the basic SE concepts based on the book from Kossiakoff et al., (2011) to define the generic system function and interactions. 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.

4.5.1 Boundary identification rule

In a SE approach it is important to identify the system boundary in the modelling. The boundary identification rule is created to identify the core functions of interest in the system 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 product being analysed. 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 a wing section as an example, the external system functions would be the system functions in the fuselage section, like “manage electrical load” and “generate conditioned air”.)

(4).The top level of system functions can be created as zones or sections separately depending on the case study scope. (For example, a landing gear bay can be defined as a top level in the functional hierarchy with the name “Landing gear bay functions”.)

4.5.2 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, only a few types can be defined in CATIA V6. Thus, 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 et al., (2011) and presented in table 4-1.

Table 4-1 Interaction definition rules mapping with generic classification

Interactions from Kossiakoff et al., (2011)		Interactions in CATIA V6		Interaction definition
Information	Signals	Functional dependency	Control	Electrical flow: system control signal
	Data		Data	Data flow: system data
Energy				power flow: electrical, hydraulic, pneumatic, thermal power Mechanical flow: air, oil, fuel, water
Materials		Physical dependency		Physical connections in 3D CAD model

4.5.3 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 4-2. An example of the rules is illustrated in figure 4-10. There are both “one to one”, “one to many”, “many to one”, and “many to many” relations in the traceability modelling.

Table 4-2 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

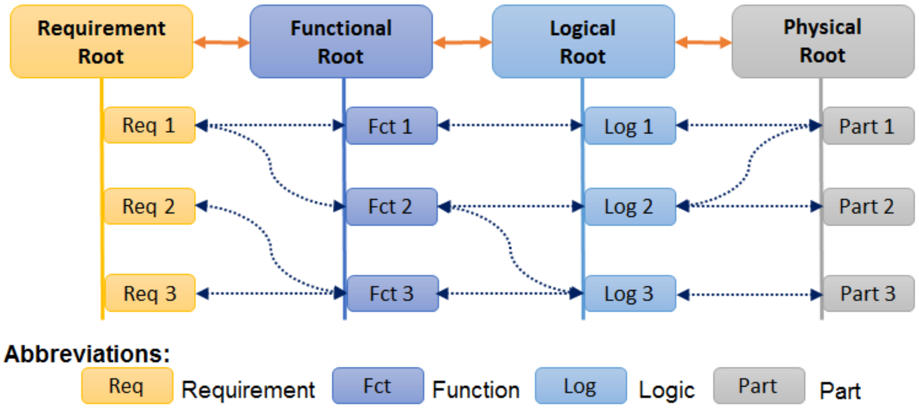


Figure 4-10 Simplified example of the traceability definition rule

4.6 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, specialised 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 4.4 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. In certification standard CS 25.952, fuel system needs to be fully tested in all working conditions. However, in the manufacturing process, those tests are allocated to different stages including assembly and flight test stage. 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 specialised 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 take place for these parallel test tasks to find the priority task from design and manufacturing factors. 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. The information, for example, can be further system control constraints from other aircraft sub-systems in the later design, and later accessibility analysis result indicating that some system components are required first.

4.7 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, 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 4-3 in a bottom-up tree structure.

Table 4-3 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

4.8 Test related to physical conditions analysis (step 4)

At early assembly integration design stage, much of the information required is not available. For instance, the detailed 3D models and assembly line environment are not available at early development stage, but they are both required for assembly sequence analysis. Hence, in this research an additional sequence analysis is developed focusing on the conditions of test related installations and facility accessibility.

In developing of the step workflow, another aspect that should be considered is the system design improvement. The overall method is built based on the RFLP engineering data source towards assembly integration needs. On the one hand, the result generated at the early design stage is only an initial feasible sequence. It will be modified and improved during later development process, or when the design is changed. On the other hand, when further assembly analysis indicates that the initial sequence is no longer feasible, it should provide feedback to the design stage to see whether it is possible to have design improvement to resolve the assembly issues.

Step 4 examines the generated initial feasible sequence using a set of questions to find whether it is still feasible under the following physical conditions:

- Ground test facilities need to be connected with the installed system equipment/components through interfaces (e.g., pipe ends, cable plugs and equipment connectors).
- For specialised technical reasons, system equipment/components need to be uninstalled and re-installed during the test processes.

It should be pointed out that the accessibility of operators is not included in the physical conditions above for the reason of information unavailability. Once more design and manufacturing information is provided in development process, the accessibility of operators should be checked in the “uninstallation/re-installation path” sub-step. The detailed workflow for step 4 is then illustrated in figure 4-11 based on these development requirements.

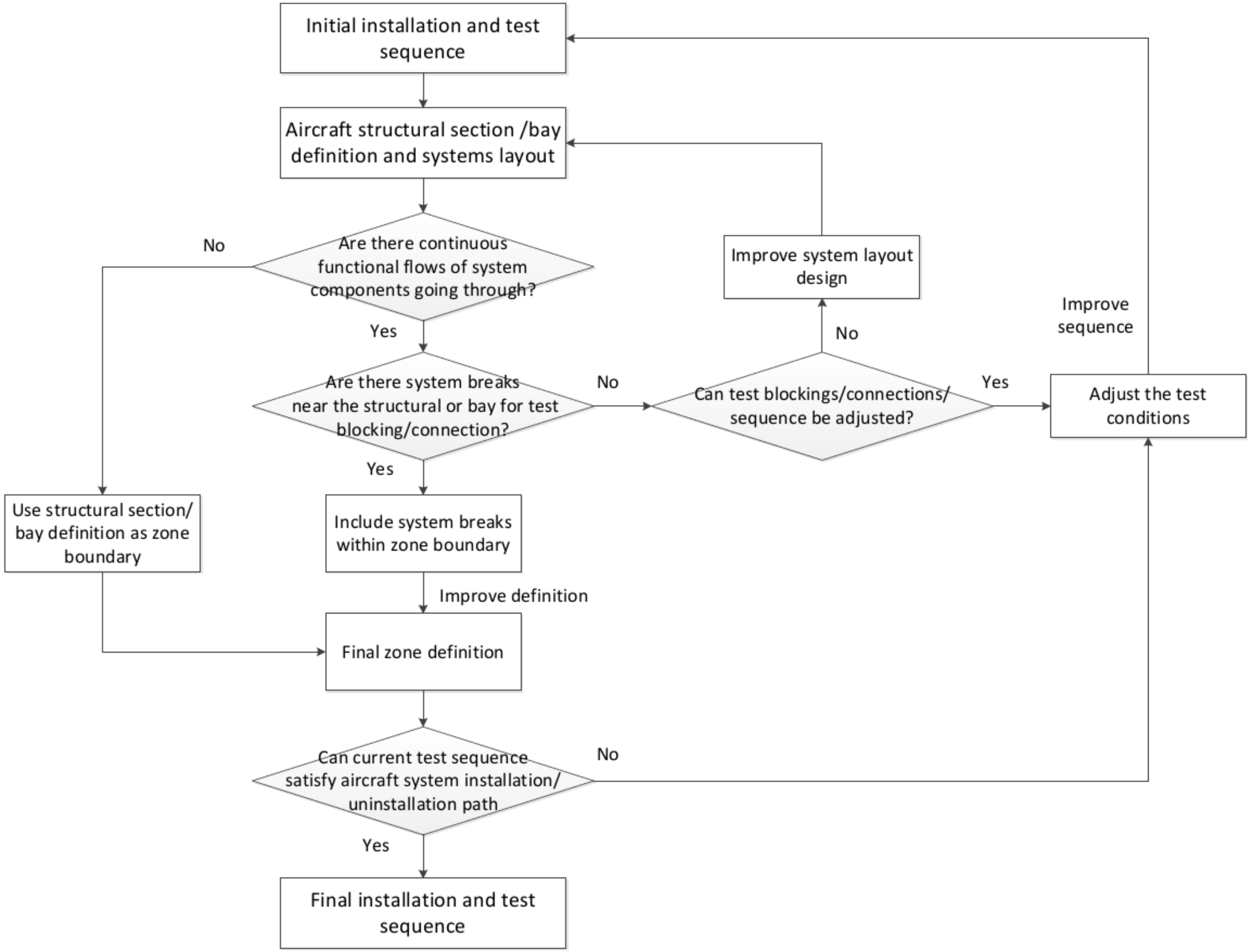


Figure 4-11 Test related physical conditions workflow

The workflow starts with the initial sequence from step 3. To make the workflow more efficient and easy to analyse the dependencies, zone partitioning concept is introduced from ZSA. It first defines the zones for detailed assembly sequence analysis (step 4-1). After that, the system interaction flows between different zones are examined following with the question of whether there are system breaks going through the zones (step 4-2). The zone partitioning question is used to ensure the zone definition is ready for detailed analysis. Then in step 4-3 the system breaks question checks the availability of system interfaces in the related zones that will be used in the tests. If there are no suitable system breaks for test blocking/ connection, it will further examine whether the test sequence can be adjusted or will the system layout design be improved. This kind of design change only refers to adjustment of the system interfaces, such as adding pipe ends or cable plugs. The step 4-3 results and answers of this question will finalise the zone partitioning in step 4-4. Finally, in step 4-5 the workflow goes to check the system installation/uninstallation path during the test. If the sequence satisfies all the required conditions, it will output the final installation and test sequence. If the answer is no, the sequence will go back to the beginning and re-run the workflow for further improvement.

4.9 Chapter summary

This chapter firstly examines the DSM and QFD using simple examples to understand their benefits and drawbacks in implementation. Then, the selection of possible tools is made after the lessons learnt from DSM and QFD. SE principles are also introduced for method development. It is found that the SE RFLP models have the potential to be a new engineering data source that support complex systems integration process design. Specified needs for the new method are given for new method development.

Then, an assembly integration sequence generation method is proposed based on the interrelationships between design and assembly within the SE RFLP framework. The proposed method has two user roles designer’s role and assembly planner’s role. The RFLP modelling is the treated as engineering data source in the design process. Then, RFLP modelling rules are developed based on the lessons learnt from DSM and QFD to ensure the requirement traceability and interaction definition. The method framework and detailed steps are also explained using simple examples. Two detailed case studies to illustrate the proposed method are presented in the following chapter.

5 CASE STUDIES

During the research, the method is developed and tested in an iterative process. Several case studies are used to test and improve the developing method. This chapter only describes the two case studies that have been used in developing of the final proposed method. Validation from academia and industry are also presented to have a preliminary evaluation of this research.

5.1 Case study 1

The first case study is developed based on the Cranfield University student group design project (GDP) aircraft E-15 (see figure 5-1), which is a preliminary design of a more electric business jet equipped with next generation of avionics (Cranfield University, 2015b). The aircraft project data includes 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.

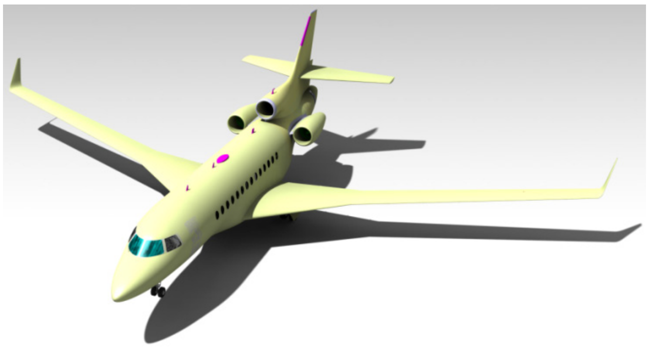
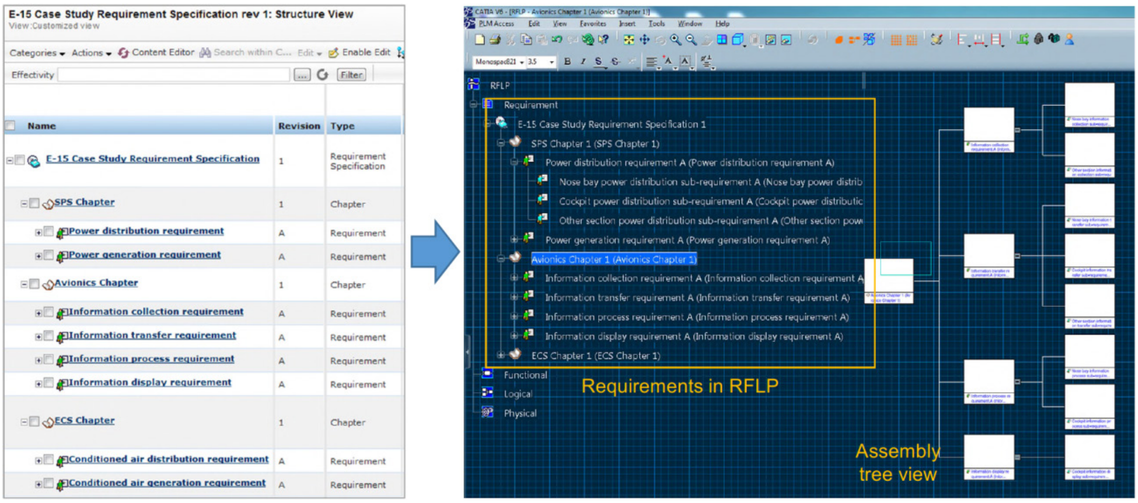


Figure 5-1 E-15 business jet (Cranfield University, 2015b)

5.1.1 Step 1 implementation: E-15 RFLP modelling

Following the method first step (as shown in figure 4-9), 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 5-2).



E-15 Case Study Requirement Specification rev 1: Structure View

View:Customized view

Name	Revision	Type
E-15 Case Study Requirement Specification	1	Requirement Specification
SPS Chapter	1	Chapter
Power distribution requirement	A	Requirement
Power generation requirement	A	Requirement
Avionics Chapter	1	Chapter
Information collection requirement	A	Requirement
Information transfer requirement	A	Requirement
Information process requirement	A	Requirement
Information display requirement	A	Requirement
ECS Chapter	1	Chapter
Conditioned air distribution requirement	A	Requirement
Conditioned air generation requirement	A	Requirement

- RFLP
  - Requirement
    - E-15 Case Study Requirement Specification 1
      - SPS Chapter 1 (SPS Chapter 1)
        - Power distribution requirement A (Power distribution requirement A)
          - Nose bay power distribution sub-requirement A (Nose bay power distrib
          - Cockpit power distribution sub-requirement A (Cockpit power distributic
          - Other section power distribution sub-requirement A (Other section pow
        - Power generation requirement A (Power generation requirement A)
      - Avionics Chapter 1 (Avionics Chapter 1)
        - Information collection requirement A (Information collection requirement A
        - Information transfer requirement A (Information transfer requirement A)
        - Information process requirement A (Information process requirement A)
        - Information display requirement A (Information display requirement A)
      - ECS Chapter 1 (ECS Chapter 1)
  - Functional
  - Logical
  - Physical

Figure 5-2 (a) Requirements in ENOVIA V6 PLM system; (b) Requirements in CATIA V6 RFLP module

Following the boundary identification rule, the case study functions are subdivided into one internal function: "nose bay section" function, and two external functions which are the "cockpit section" function and "other sections" function. Figure 5-3 (a) shows part of the system functions design as a 2D block diagram. Following the classification definition from (Kossiakoff et al., 2011), 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 recognised 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 5-3 (b) shows the functional modelling results with functions of three top-level sections and interactions between them. Figure 5-3 (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 platform. Figure 5-4 (a) shows all the RFLP models with the activated logical modelling view and physical assembly model at background. The 3D physical model in figure 5-4 (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.

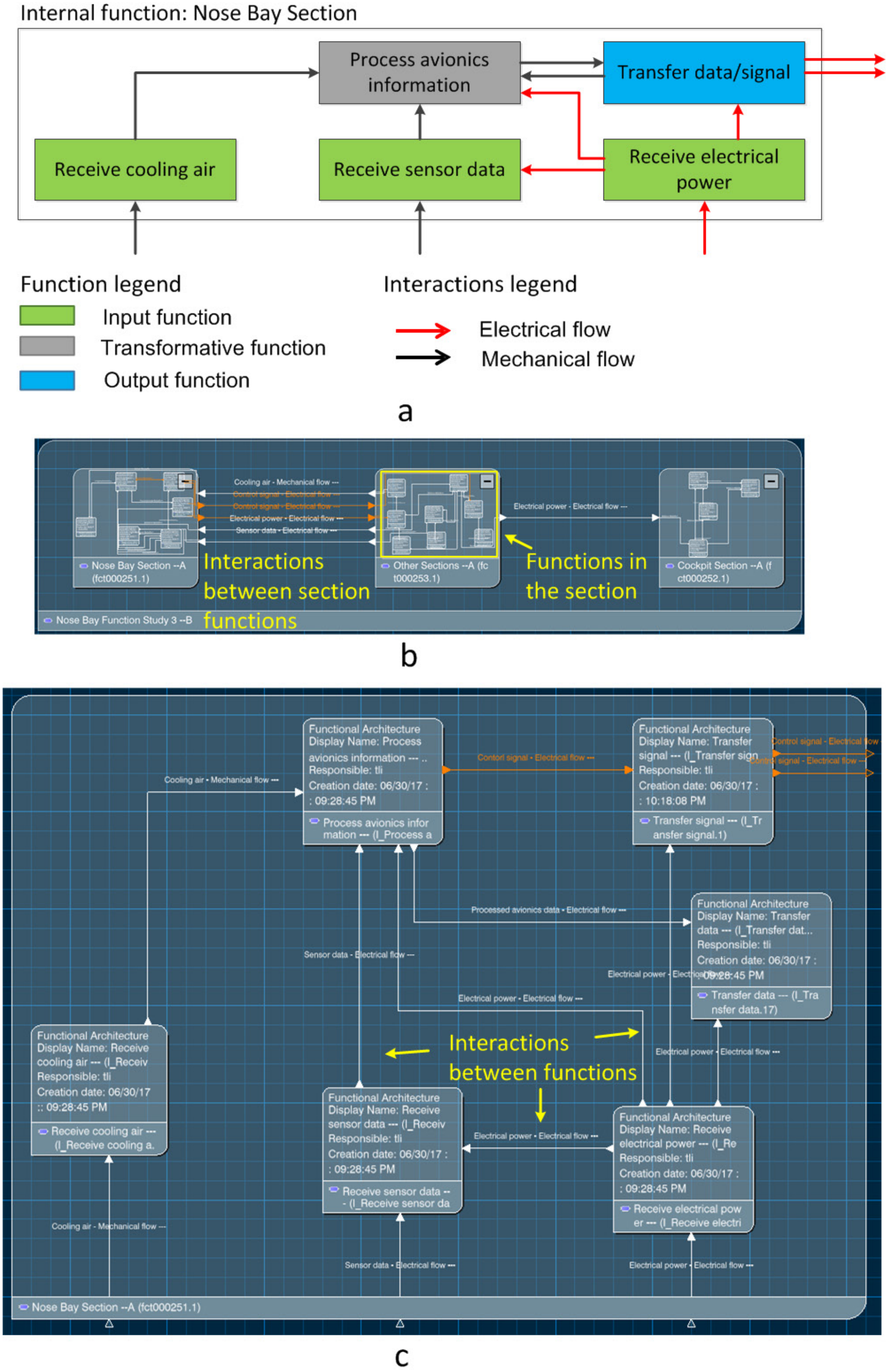


Figure 5-3 (a) Extract from nose bay section as internal function in 2D block diagram; (b) Internal and external functional models in CATIA V6; (c) Nose bay section functional model and interaction

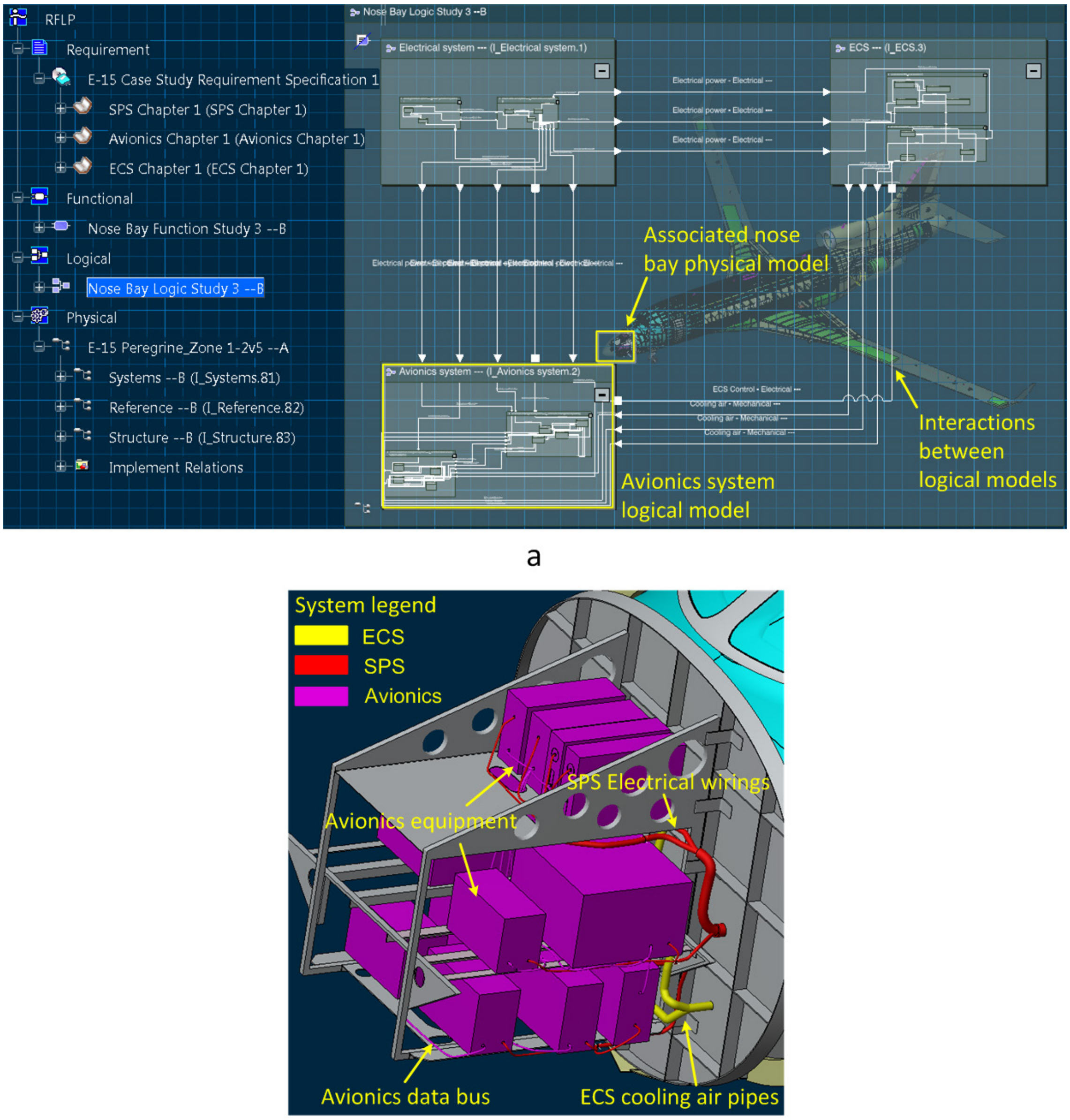
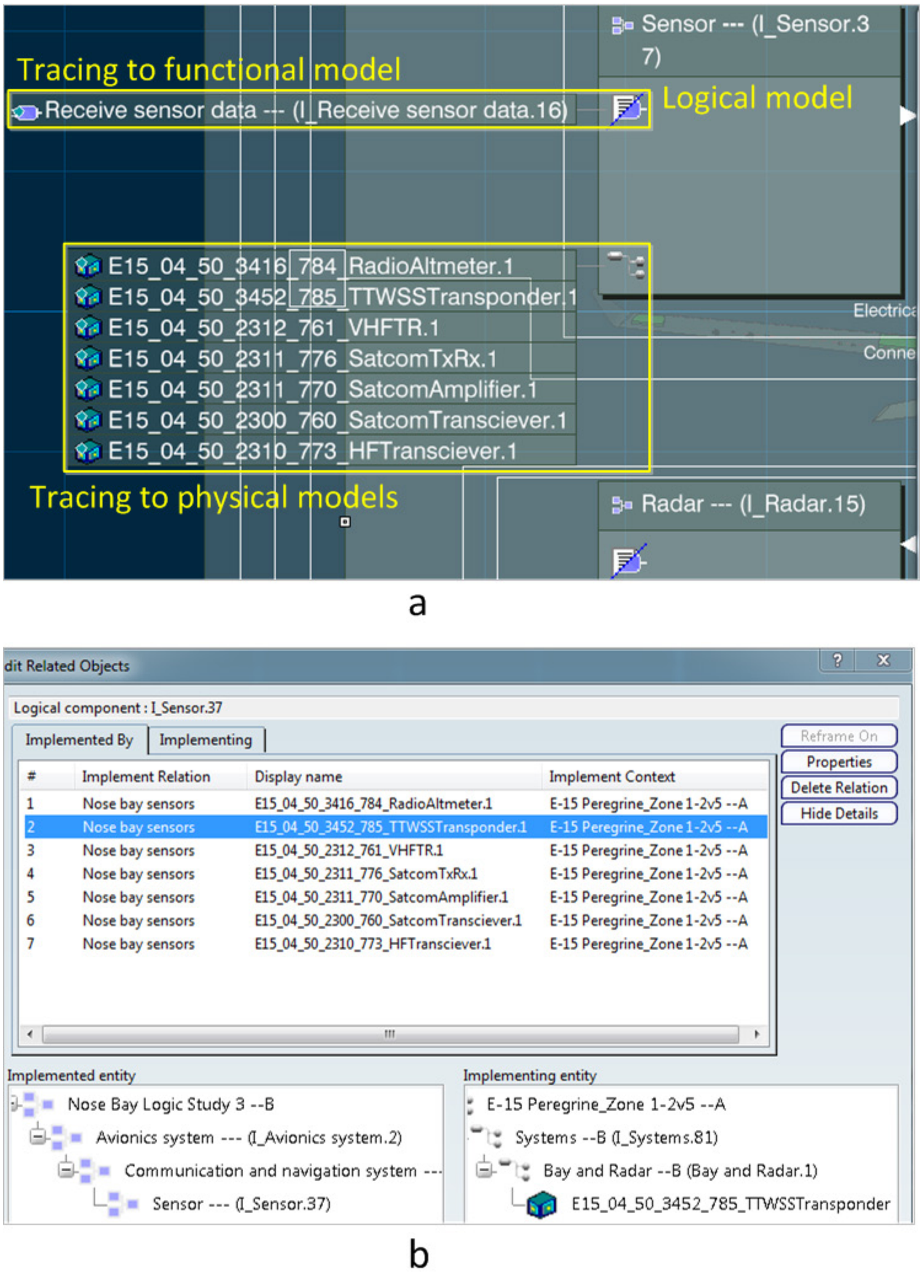


Figure 5-4 (a) RFLP models with activated logical view; (b) 3D physical system assembly models of nose bay section

The traceability links are embedded in the models using the traceability definition rule through the overall modelling process. Figure 5-5 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 complete representation of the E-15 functional and logical models is provided in Appendix B.1.



Logical component : I_Sensor.37

#	Implement Relation	Display name	Implement Context
1	Nose bay sensors	E15_04_50_3416_784_RadioAltmeter.1	E-15 Peregrine_Zone1-2v5 --A
2	Nose bay sensors	E15_04_50_3452_785_TTWSSTransponder.1	E-15 Peregrine_Zone1-2v5 --A
3	Nose bay sensors	E15_04_50_2312_761_VHFTR.1	E-15 Peregrine_Zone1-2v5 --A
4	Nose bay sensors	E15_04_50_2311_776_SatcomTxRx.1	E-15 Peregrine_Zone1-2v5 --A
5	Nose bay sensors	E15_04_50_2311_770_SatcomAmplifier.1	E-15 Peregrine_Zone1-2v5 --A
6	Nose bay sensors	E15_04_50_2300_760_SatcomTransciever.1	E-15 Peregrine_Zone1-2v5 --A
7	Nose bay sensors	E15_04_50_2310_773_HFTransciever.1	E-15 Peregrine_Zone1-2v5 --A

Implemented entity

- Nose Bay Logic Study 3 --B
  - Avionics system --- (I_Avionics system.2)
    - Communication and navigation system ---
      - Sensor --- (I_Sensor.37)

Implementing entity

- E-15 Peregrine_Zone 1-2v5 --A
  - Systems --B (I_Systems.81)
    - Bay and Radar --B (Bay and Radar.1)
      - E15_04_50_3452_785_TTWSSTransponder

Figure 5-5 (a) Example of traceability links; (b) Detailed traceability information

5.1.2 Step 2 implementation: E-15 test breakdown generation

Step 2 of the process generates the hierarchical test breakdown from the RFLP model. As mentioned in figure 4-7, 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 5-1 with influence on assembly integration and test solutions from the author's industry background.

Table 5-1 System constraints in the E-15 nose bay 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 5-3 (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 5-6 (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 it is found that 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 interaction links between other two tests are removed. Thus, the test stages are decided and the adapted test block diagram is re-sorted and deployed to logical components through the functional and logical traceability links in figure 5-6 (b).

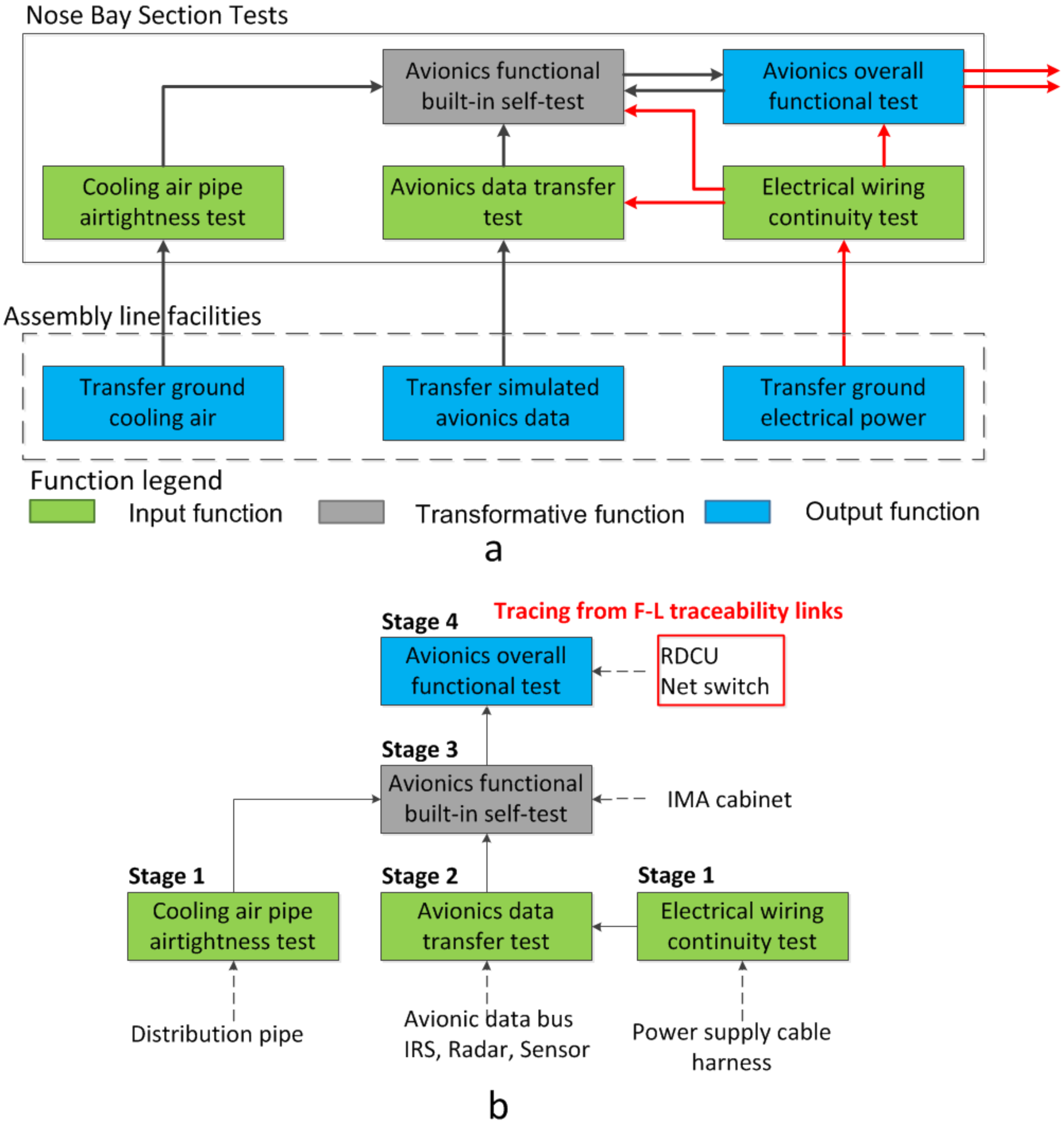


Figure 5-6 (a) Adapted test block diagram based on figure 5-3(a); (b) Test breakdown with logical components

5.1.3 Step 3 implementation: E-15 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

5-7 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 5-7 (b), the numbering of the physical items shown in figure 5-5 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.

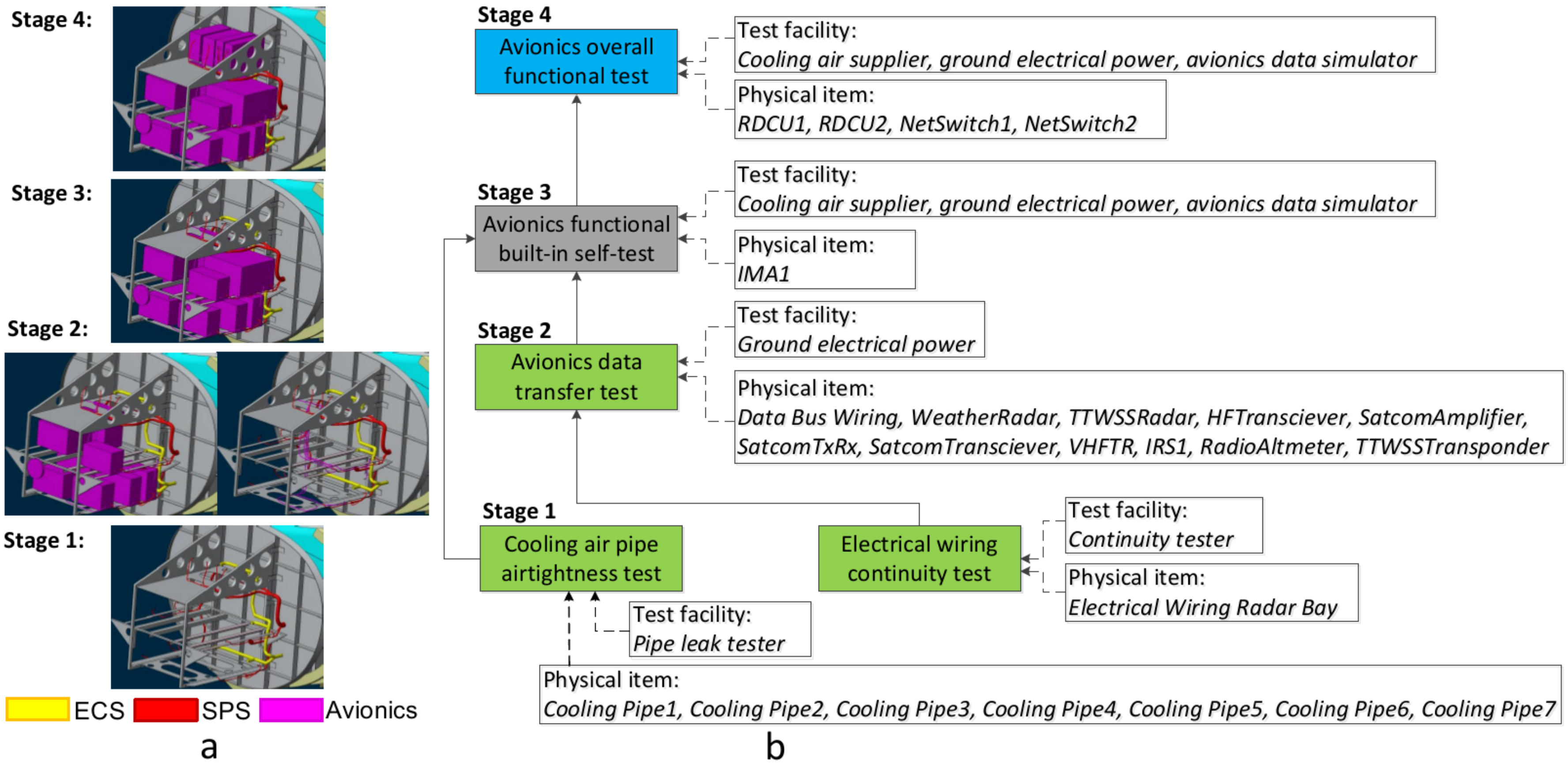
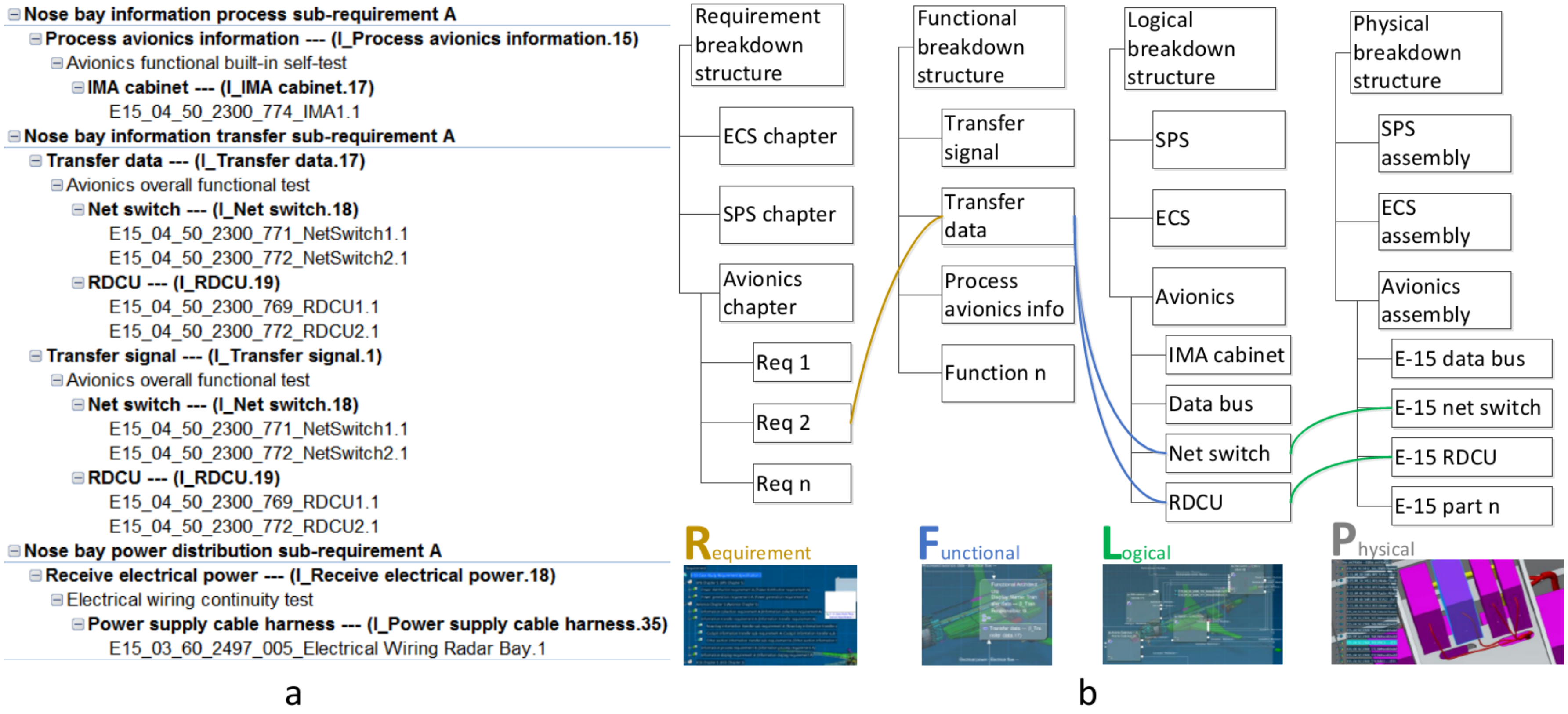


Figure 5-7 (a) Integration sequence in 3D assembly view; (b) Detailed physical installation components with associated test tasks and facilities

Figure 5-8 shows part of the extracted requirement traceability results from the RFLP models that link to test tasks (a full version of the extracted E-15 traceability is provided in the Appendix B.2). 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 5-6 (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 research, 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 much more robust manufacturing process, in which the aircraft system function is tested after certain installations to minimise the risk of errors and rework.



⊟ **Nose bay information process sub-requirement A**
  ⊟ **Process avionics information --- (I_Process avionics information.15)**
    ⊟ Avionics functional built-in self-test
      ⊟ **IMA cabinet --- (I_IMA cabinet.17)**
        E15_04_50_2300_774_IMA1.1
⊟ **Nose bay information transfer sub-requirement A**
  ⊟ **Transfer data --- (I_Transfer data.17)**
    ⊟ Avionics overall functional test
      ⊟ **Net switch --- (I_Net switch.18)**
        E15_04_50_2300_771_NetSwitch1.1
        E15_04_50_2300_772_NetSwitch2.1
      ⊟ **RDCU --- (I_RDCU.19)**
        E15_04_50_2300_769_RDCU1.1
        E15_04_50_2300_772_RDCU2.1
  ⊟ **Transfer signal --- (I_Transfer signal.1)**
    ⊟ Avionics overall functional test
      ⊟ **Net switch --- (I_Net switch.18)**
        E15_04_50_2300_771_NetSwitch1.1
        E15_04_50_2300_772_NetSwitch2.1
      ⊟ **RDCU --- (I_RDCU.19)**
        E15_04_50_2300_769_RDCU1.1
        E15_04_50_2300_772_RDCU2.1
⊟ **Nose bay power distribution sub-requirement A**
  ⊟ **Receive electrical power --- (I_Receive electrical power.18)**
    ⊟ Electrical wiring continuity test
      ⊟ **Power supply cable harness --- (I_Power supply cable harness.35)**
        E15_03_60_2497_005_Electrical Wiring Radar Bay.1

Figure 5-8 (a) Part of extracted requirement traceability links with test tasks; (b) Simplified illustration of case study requirement traceability

5.1.4 Step 4 implementation: E-15 test related physical conditions analysis

The sub-steps include: zone partitioning, functional flow check, system breaks check, zone finalisation, and installation/uninstallation path check.

4-1. Zone partitioning

Since a zone is normally defined based on structural bays, this case study has only one zone the nose bay (3D CAD model see figure 5-4 (b)).

4-2. Functional flow check

In the nose bay zone, the functional flow includes: the electrical flows, which are avionic control signal and data, and electrical power; the mechanical flow in this zone is the ECS cooling air.

4-3. System break check

The breaks of electrical flow include the cable plugs used for continuity test and test equipment connection, while the breaks for mechanical flow are ECS pipe ends for airtightness test blocking and test equipment connection.

4-4. Zone finalisation

The continuous functional flows have been detected in step 4-2. As the tests related work is actually part of the assembly sequence, and some system breaks behind the airframe are used for test connection, such system breaks should be included in the nose bay zone as part of the test related physical conditions. Hence, the following system components are added in the nose bay zone (see figure 5-9):

- Electrical power cable harnesses to the next break plugs behind the airframe
- ECS pipes to the next break ends behind the airframe

4-5. Installation/uninstallation path check

The initial generated sequence is examined by the test related installation/uninstallation path to find whether it is still feasible. The check results are shown in table 5-2.

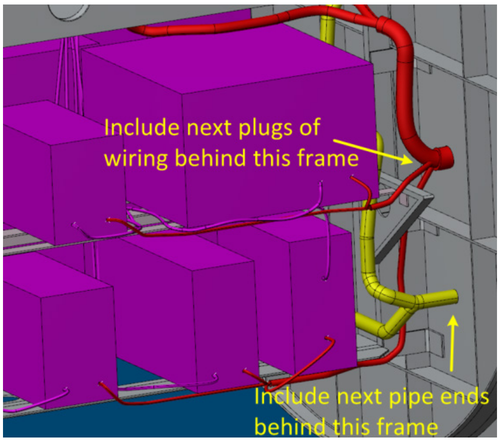


Figure 5-9 Clarification of the zone boundary

Table 5-2 Initial sequence examination result

Question	Is the sequence satisfied with the system installation/uninstallation path?		
Stage	Test task	Check result	Action
1	Cooling air pipe airtightness test	Yes, the cooling air users (avionics equipment) are installed after the airtightness test	
1	Electrical wiring continuity test	Generally yes, the electrical power users (avionics equipment) are installed after the continuity test. But the cooling air pipes may cause clash problem if they are all installed before electrical wirings	Sub-divide the sequence and make wiring as prior work before piping
2	Avionics data transfer test	Generally yes, but data bus should be installed before other avionics equipment. The test should be performed after the installation of related equipment (to have the final bend layout for data transferring performance test).	Sub-divide the stage sequence and make data bus as prior work
3	Avionics functional built-in self-test	Yes, the bay is open access, thus IMA cabinet can be installed before the test	
4	Avionics overall functional test	Yes, the bay is open access, thus RDCUs and network switches can be installed before the test	

The analysis results in table 5-2 indicate that the initial sequence should have some adjustment to fulfil the test related physical conditions. Current electrical and data-bus wiring sequences cannot satisfy the system installation/uninstallation path. An improved sequence is produced by moving electrical and data-bus wiring as sub-assemblies before other components installations (see figure 5-10).

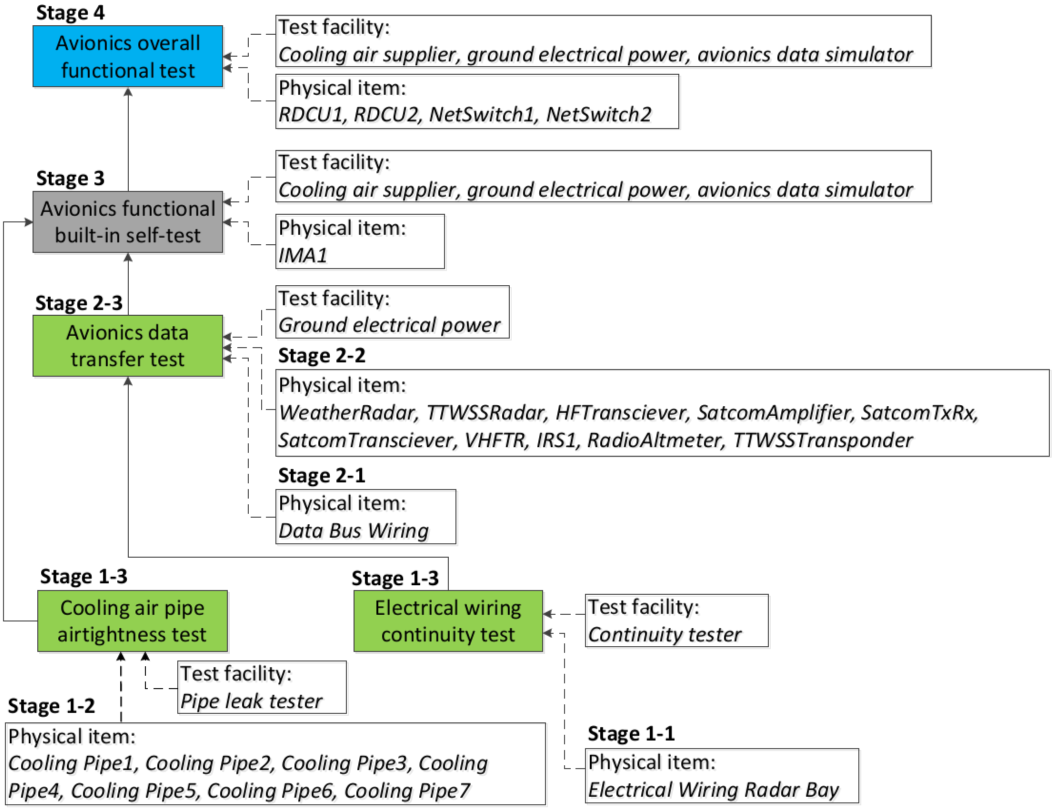


Figure 5-10 Improved assembly integration sequence

5.1.5 Summary of the E-15 case study results

The first case study shows preliminarily that the proposed method can produce a feasible assembly integration sequence. The case study result also 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. However, the first case study focuses more on implementation of the modelling rules and model reuse. The proposed method needs to be further tested on a more complicated case study that is closer to industrial implementation.

5.2 Case study 2

The second case study is based on a design similar to Boeing 777 wing section systems based on published sources and aircraft manuals (Boeing Commercial Airplanes, 2015; Langton et al., 2009; Lufthansa Technical Training GmbH, 2013; Moir and Seabridge, 2008). The selected systems have more system components, more complicated layout in the wing section, and more multidisciplinary interactions than the first case study. This case study includes the following elements of the B777 design:

- Aircraft surface geometry and wing section structure layout
- Wing section fuel system
- Wing section environment control system (ECS)
- Wing section electrical power system
- Wing section avionics system (data bus wiring only)

These systems are managed under the federated controlled system architecture.

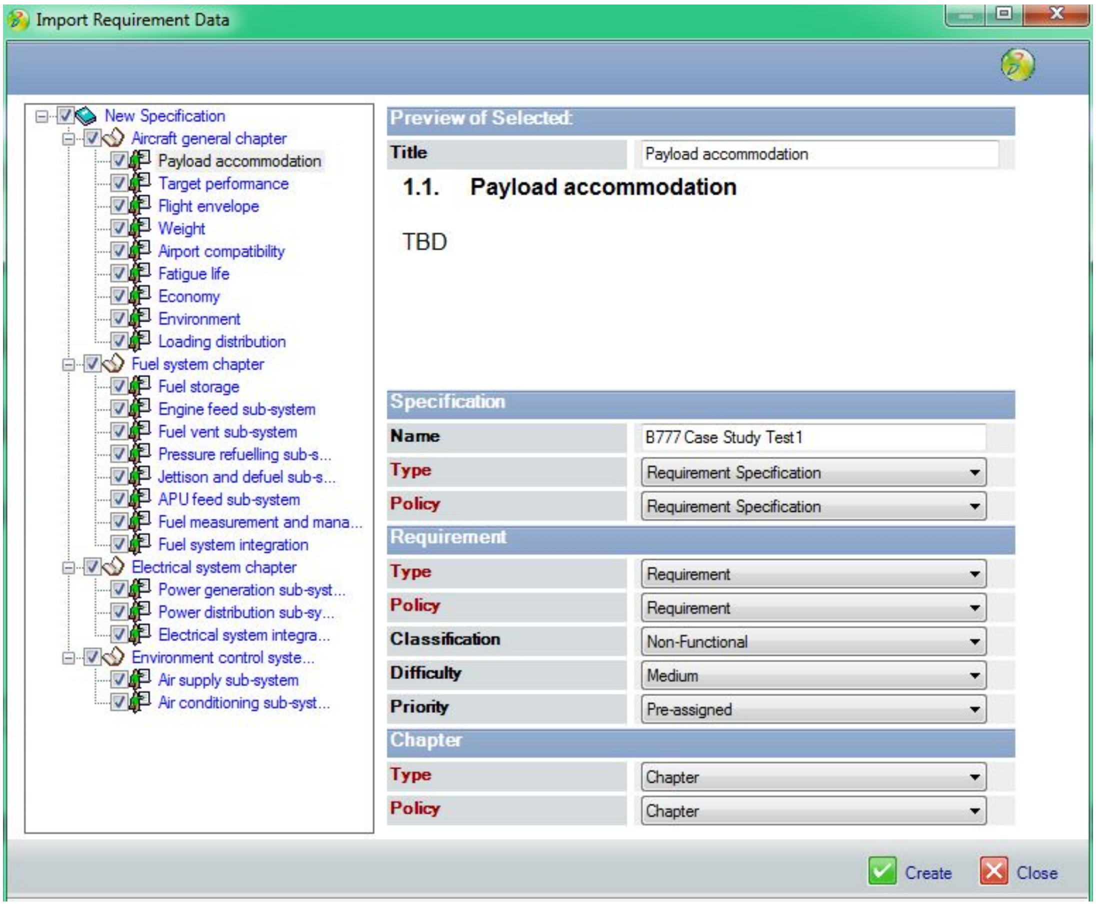
5.2.1 Step 1 implementation: B777 RFLP modelling

The four sub-steps of the RFLP modelling are presented separately with modelling results due to the large number of modelling items.

5.2.1.1 Requirements modelling

This case study aims to test the method in an industry-like environment. Hence, the requirements are created in a template first by picking up relevant system requirements from the EASA CS-25 (European Aviation Safety Agency, 2007), and then uploaded into the ENOVIA V6. The full version of the requirement template and detailed requirements content for this case study are shown in the Appendix C.1.

It is found in the requirement capture process that some aircraft system design specifications are from aircraft level requirements first and then specified to detailed requirements in system level requirement. For instance, the fuel tank volume is stated as part of the customer requirement in the range requirement at aircraft level, and given more detailed specifications in fuel system design requirement. In coordination with the R-F-L-P requirements decomposition and tracing principles proposed in this project (see section 4.5.3), the structure of requirement template includes four chapters for the second case study: aircraft general, fuel system, electrical system, and environment control system. Thus, in the requirement modelling different level of requirements can be connected and traced in the PLM system by expanded traceability links in requirements engineering. Figure 5-11 shows the created requirement chapters and sub-requirements that have been defined for the B777 case study when imported from the requirements document (see Appendix C.1.2) into the PLM system using the ENOVIA requirement capture toolkit.



- ☑ New Specification
  - ☑ Aircraft general chapter
    - ☑ Payload accommodation
    - ☑ Target performance
    - ☑ Flight envelope
    - ☑ Weight
    - ☑ Airport compatibility
    - ☑ Fatigue life
    - ☑ Economy
    - ☑ Environment
    - ☑ Loading distribution
  - ☑ Fuel system chapter
    - ☑ Fuel storage
    - ☑ Engine feed sub-system
    - ☑ Fuel vent sub-system
    - ☑ Pressure refuelling sub-s...
    - ☑ Jettison and defuel sub-s...
    - ☑ APU feed sub-system
    - ☑ Fuel measurement and mana...
    - ☑ Fuel system integration
  - ☑ Electrical system chapter
    - ☑ Power generation sub-syst...
    - ☑ Power distribution sub-sy...
    - ☑ Electrical system integra...
  - ☑ Environment control syste...
    - ☑ Air supply sub-system
    - ☑ Air conditioning sub-syst...

Preview of Selected:

Title: Payload accommodation

1.1. Payload accommodation

TBD

Specification

Name: B777 Case Study Test1
Type: Requirement Specification
Policy: Requirement Specification

Requirement

Type: Requirement
Policy: Requirement
Classification: Non-Functional
Difficulty: Medium
Priority: Pre-assigned

Chapter

Type: Chapter
Policy: Chapter

Figure 5-11 B777 Requirements structure when importing into PLM system

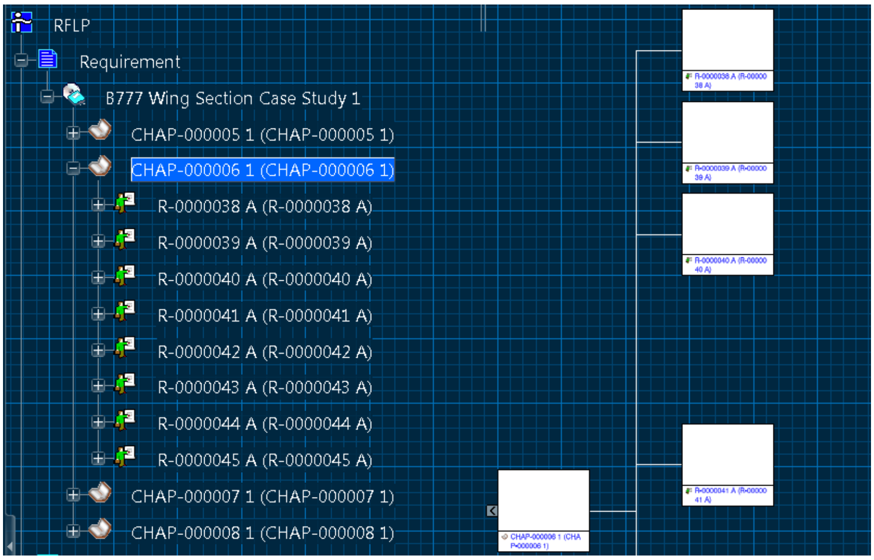


Figure 5-12 Part of the B777 requirements in CATIA V6 environment

The requirement numberings are automatic created by the PLM system after importing, and can be obtained in CATIA V6 as shown in figure 5-12.

5.2.1.2 Functional modelling

The wing section systems are the main modelling objectives in this case study. It is then defined as the internal function following the boundary identification rule. However, the wing section only presents part of the major system functions, four external functions are identified as: functions from other structural sections, powerplant, environment, and ground. In the system design process, there are many functions of major systems decided through the requirements decomposition process. These functions can be further identified as input, transformative and output functions using the classification from Kossiakoff et al., (2011). These functions may exist both in the main research scope internal function and the associated external functions. For example, the requirement "FQIS (Fuel Quantity Indicating System) wiring" is decomposed to several functions including "receive control signal", "receive fuel data", "transfer control signal", "transfer fuel data". The function "receive fuel data" is both available in the "wing section" function and "other section" function. Besides, the function "provide working environment" is decomposed from the requirement "FOD (Foreign Object Damage) safe" for APU feed sub-system. This function does not actually have an interaction type for "Apply APU feed" function, since some requirements directly go to user operation manuals, or be treated as quality control requirements. Functions decomposed from such requirements do not link to specific logical components in later logical modelling. However, in the B777 case study, it is kept in the functional modelling as a design driver for system design and assembly process planning. The interactions are then defined in a 2D diagram using the interaction definition rule (see section 4.5.2) as shown in figure 5-13 (A larger figure with detailed external functions is provided in the Appendix C.2.1).

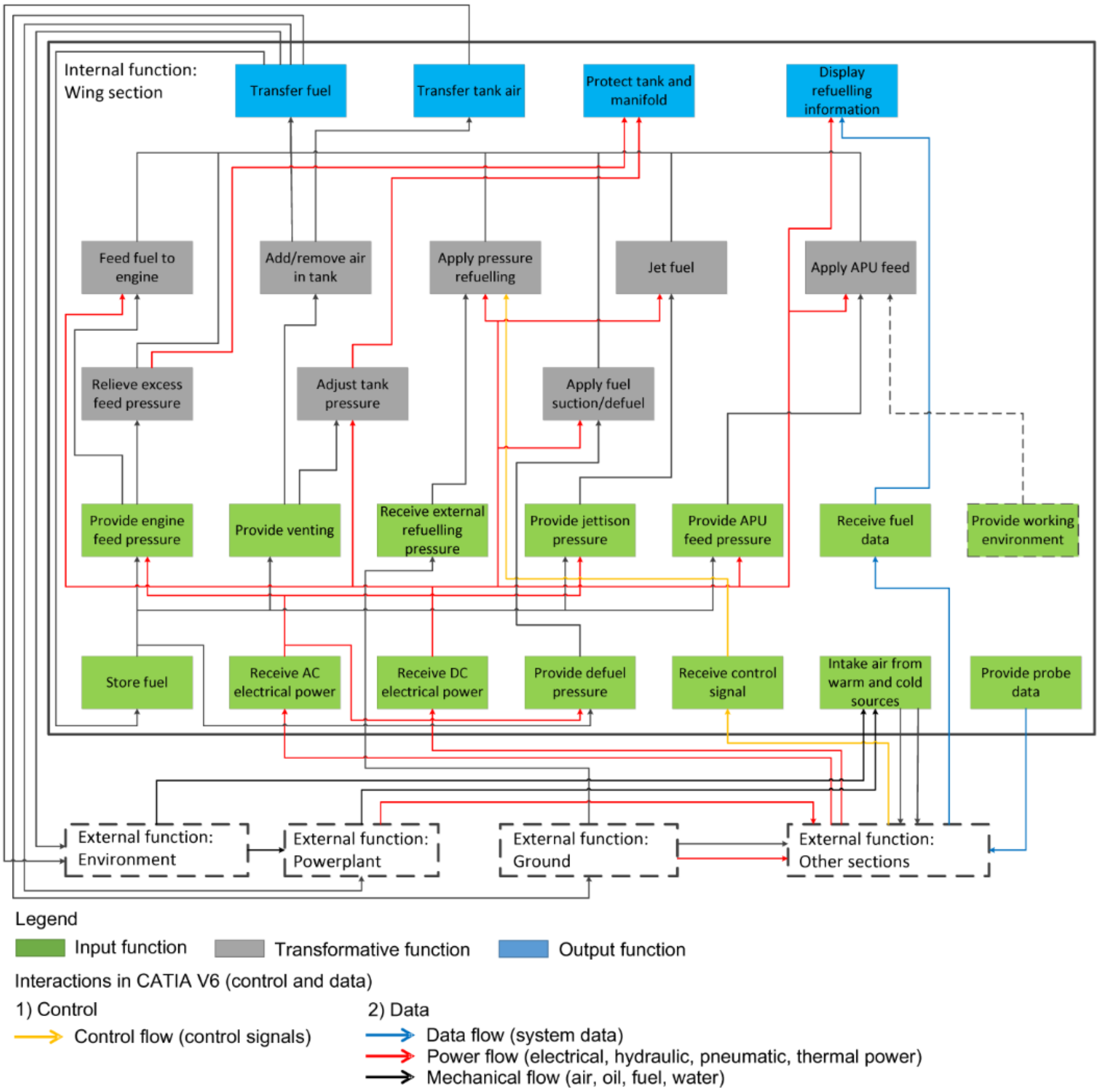


Figure 5-13 2D block diagram of the B777 functional model (with simplified external functions)

In figure 5-13, aircraft functions are grouped as input, transformative and output functions by applying Kossiakoff et al. (2011) SE function grouping principles. Interactions are classified as two main catalogues “Control” and “Data”. “Control” interactions refer to the system control signals between functional blocks, while “Data” interactions include system data flow, system driving power flow and mechanical flow.

Then a 2D block diagram is created in the CATIA V6 functional modelling module to provide detailed interactions definition as shown in figure 5-14. The internal and external function definitions follow the system of systems concept, which is easier for users to understand the dependencies between functions (A sample definition of interactions and the detailed functional modelling results refer to Appendix C.2.2 and C.2.3).

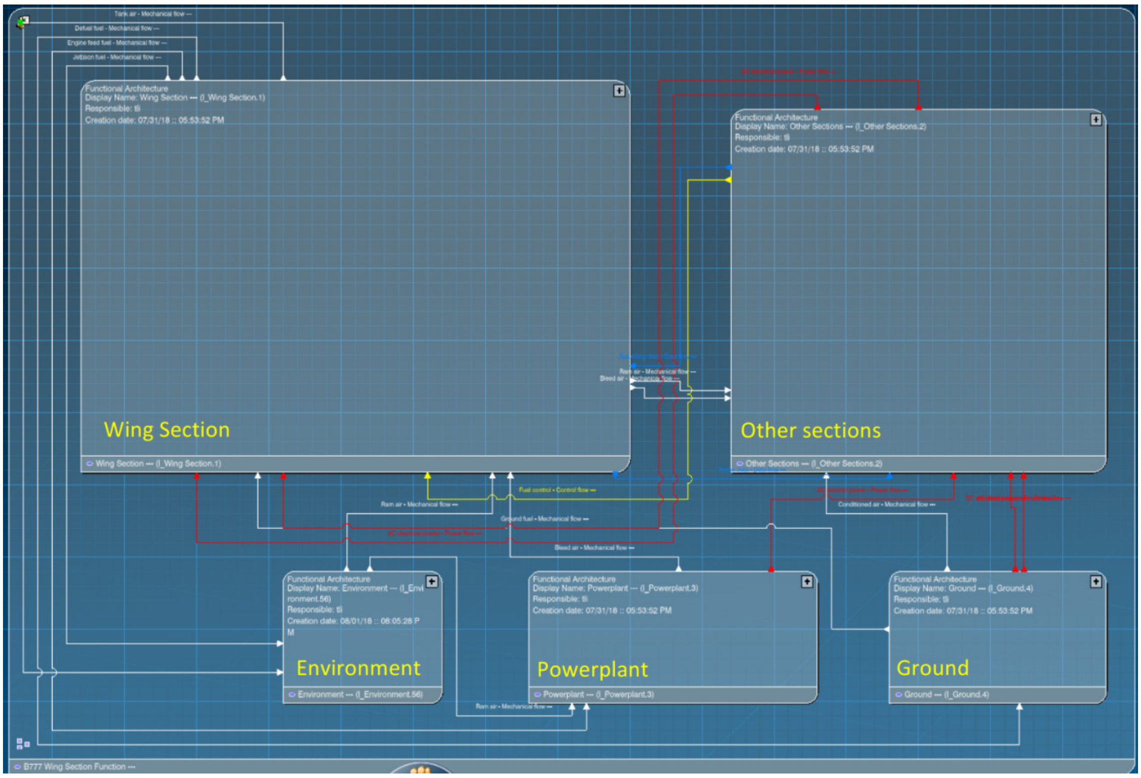


Figure 5-14 Functional modelling result in CATIA V6 (top-level view)

5.2.1.3 Logical modelling

The logical models describe how the wing section systems are composed as a result of the system functions decompositions. The B777 case study is much more complicated than the first E-15 nose bay. In the logical modelling, it is interesting to find some system functions in the functional model are finally allocated to some different logical systems. The two wing section functions “receive control signal” and “receive fuel data” are created to describe the fuel control and information display. They are actually partly allocated to the “wing leading edge data bus”, which is a logical component of the avionics system. The function “receive fuel data” is also from the requirement of “fuel measurement and management” (see figure 5-11 and requirement document “section 2.7” in the Appendix C.1.2). There are other similar situations found in this case study, which are considered as the evidence of the “shared aircraft system functions and interconnectedness design” stated by Seabridge (2010a). The system logical hierarchy is shown in table 5-3 and a brief system composition is given in figure 5-15 (more detailed logical models are given in the Appendix C.3). It should be noticed that some logical components like the electrical power generators in table 5-3 are out of the case study scope, they are kept in the logical modelling to have complete relevant dependencies of the selected aircraft systems.

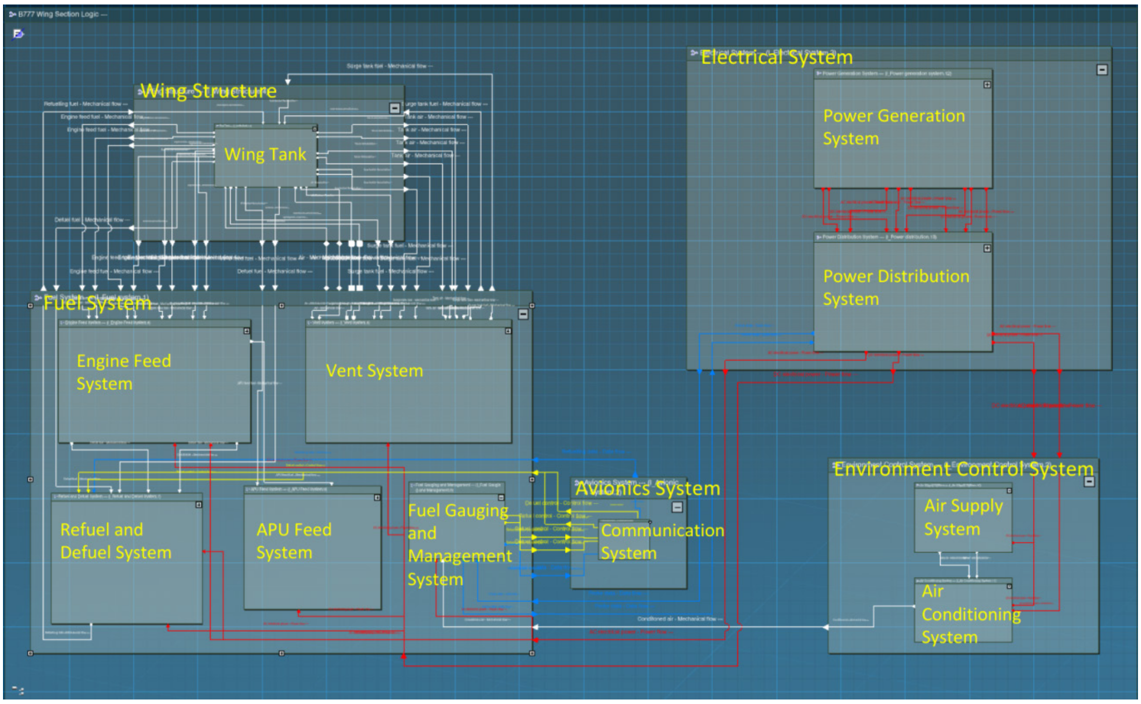


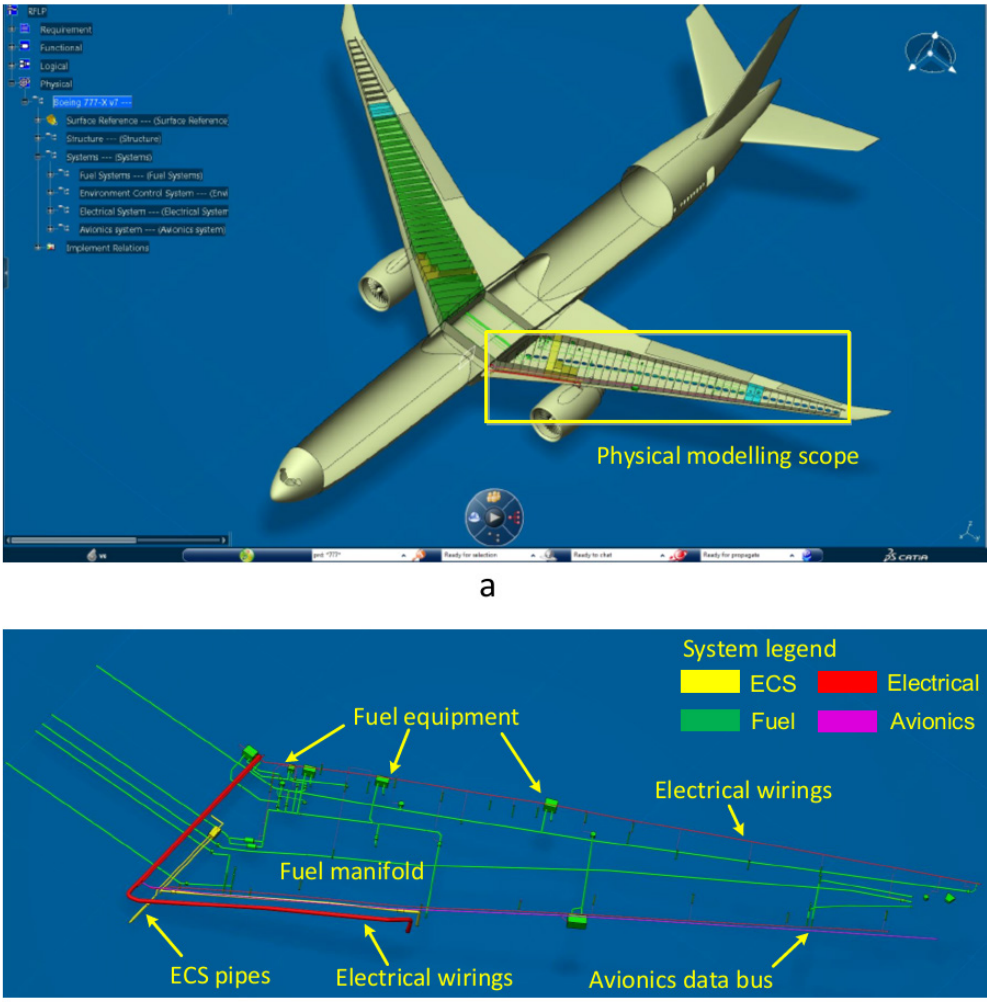
Figure 5-15 Logical modelling result in CATIA V6 (top and second level view)

Table 5-3 B777 case study system hierarchy in logical modelling (including other structural section system logical components and structural tanks)

Major system	Sub-system	Logical components
Fuel	Vent	Vent pipe, float drain valve, float actuated vent valve, check vale, re-settable pressure relief valve, NACA Scoop/Flame arrestor, main tank drain pipe
	Engine feed	Forward feed pump, override/jettison pump, engine feed pipe, cross-feed valve, suction feed valve, engine feed SOV, feed NRV, aft feed pump, other side feed pipe
	Refuel and defuel	Fuel jettison nozzle, refuel valve, refuel pipe, manifold drain valve, refuel/defuel station, jettison valve, jettison pump, defuel and jettions pipe, defuel SOV, defuel valve
	Fuel gauging and management	Fuel probes, fuel quantity processing unit
	APU feed	APU feed SOV, APU feed pipe, APU feed DC pump, APU feed NRV, isolation valve
ECS	Air supply	Bleed air pipe, air filter, ram air intake pipe, bleed air SOV, bleed air filter
	Air conditioning	Air conditioning pack, air distribution pipe
Electrical	Power generation	Left IDG, right IDG, backup generators, VSCF converter, APU generator, RAT generator, secondary external power, primary external power, power generation cable harness, left TRUs, right TRUs
	Power distribution	Left primary power panel, auxiliary power panel, right primary power panel, left power management panel, ground servicing/handling panel, standby power management panel, right power management panel, power distribution cable harness, fuel tank cable harness
Avionics	Communication	Wing leading edge data bus, fuselage data bus
Wing structure	Fuel tank	Left centre tank, left main tank, left surge tank, interconnect tube, right centre tank, right main tank, right surge tank

5.2.1.4 Physical modelling

The physical modelling is finished by creating 3D CAD models of the aircraft port wing section in the CATIA assembly design module. In the design process, the physical models are specified from the logical models that enable to build the real physical product. The B777 physical models include detailed 3D CAD of the major systems in the port wing section, and structural surface and port wing layouts of the aircraft. Access panels at the bottom surface of wing structure are created as well to allow further assembly analysis using the method step 4. The 3D assembly master model is shown in figure 5-16 (a), and the detailed major systems 3D models are presented in figure 5-16 (b). The physical layouts in this 3D model are supposed to be designed as a solution of the logical model in the standard RFLP modelling process. In this case study, the physical assembly design uses B777 system design book, maintenance guide, training manual and other published B777 system assembly layout information as reference (Air Accidents Investigation Branch, 2009; Boeing Commercial Airplanes, 2015; Langton et al., 2009; Lufthansa Technical Training GmbH, 2013; McWha, 1993). However, the results in figure 5-16 are still approximate representations of the real aircraft, as many of the assembly details are based on the author’s inference.



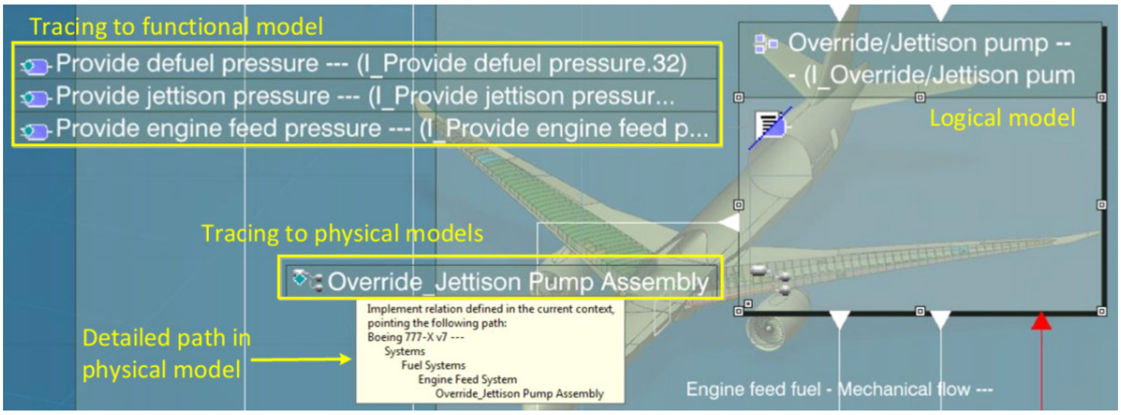
a

b

Figure 5-16 (a) B777 3D physical model; (b) Detailed port wing systems physical model without structure

5.2.1.5 Traceability link modelling

The traceability links are created through the step 1 process. As mentioned in requirement modelling, traceability links actually consist of two parts in the software implementation. The first part is the links between RFLP models that applied in this research, and the other part is the links created in requirement engineering which trace different kind of requirements, such customer requirements and user requirements. Although this research only concentrates on developing and reusing the RFLP traceability links, as the data are all managed in the same PLM system, it is possible to expand the linking information in RFLP models to the links in requirement engineering. The traceability definition process is the same as case study 1, and they are embedded in RFLP models following the traceability definition rule. Figure 5-17 shows the forward and backward tracing information of the logical component “Override/Jettison pump”. A detailed tracing path can be presented in the model as well.



Implement relation defined in the current context,
pointing the following path:
Boeing 777-X v7 ---
Systems
Fuel Systems
Engine Feed System
Override_Jettison Pump Assembly

Figure 5-17 Example of a logical component traceability links in CATIA V6

This is the end of step 1 RFLP modelling, the models are ready to be reused in the following assembly deployment and sequence generation. The complete B777 requirement traceability links are provided in Appendix C.5. The extracted traceability links are sorted into two versions: one for requirement decomposition which is mostly used in design stage, another one for test backward tracing which would help assembly planner understand the associated design requirements.

5.2.2 Step 2 implementation: B777 test breakdown generation

The method step 2 begins with checking the unavailable interactions in the functional model. It then re-builds part of the system interactions by using ground test solutions to allow a feasible production verification test. Compared to the E-15 case study, which is considered as part of the final assembly line work, the B777 wing assembly line has more assembly constraints because it is an earlier assembly stage than final assembly. The B777 wing assembly line constraints and possible test solutions are then concluded in table 5-4.

Table 5-4 System constraints in the wing assembly line and solutions

No.	System integration constraints	Influence	Test solution
1	No power plant running	Main electrical power generation not available	Use ground electrical power
		Engine bleed air not available, leads to fuel tank vent pressure and air conditioning work working not available	Use ground pressurised air for fuel tank vent
			Use ground conditioning air
2	No ram air input at assembly line	Air conditioning pack working not available	Use ground conditioning air
3	No fuel in the fuel tank	Fuel system working and control not available	Use ground pressurised air to replace fuel to test the overall system
			Use input voltage check to avoid extended dry running of fuel pumps
			Use specialised equipment to control the system
		Fuel quantity data not available for system control	Use simulated fuel quantity from test equipment

The 2D block diagram of system functions in figure 5-13 is examined by the constraints in table 5-4, and finds the original functions in the external “Environment”, “Powerplant” and “Ground” are not available. Since it is the wing assembly line, the “Other section” external function is not available as well. As a result of that, most of the interactions between the functional models are not available. The wing section functions cannot be performed any functional verifications tests, which would leave high risks at later final assembly and flight test stages. The interactions of “Intake air from warm and cold sources” and “Provide probe data” are associated more with external functions than the wing section functions, and parts of their interactions are also replaced by ground facilities and test equipment. Hence, to some extent the two functions are intendent with the wing section functions. By applying the test solutions in table 5-4, the adapted ‘function’ hierarchy is shown in figure 5-18. This equipment can provide fuel system control by simulating part of the FQPU (Fuel Quantity Processor Unit) functions. Power sources are now provided by assembly line ground facilities.

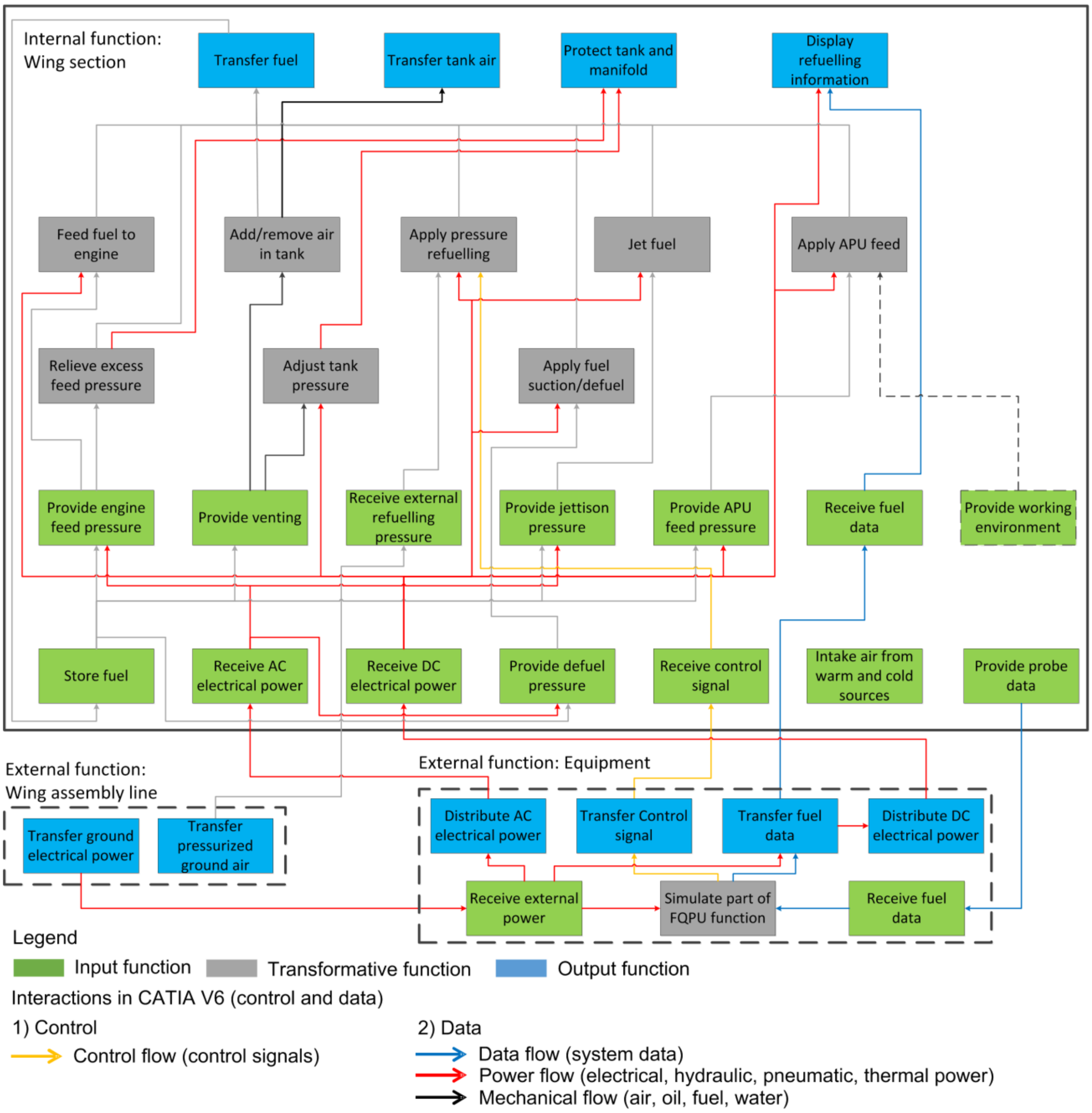


Figure 5-18 Adapted 'function' hierarchy with wing assembly line constraints

Then a 'test' hierarchy is produced by arranging production test tasks for the adapted functions using the principles explained in section 4.4 (see figure 5-19). Following the method step 2-4, these external functions are hidden to leave the 'test' hierarchy only.

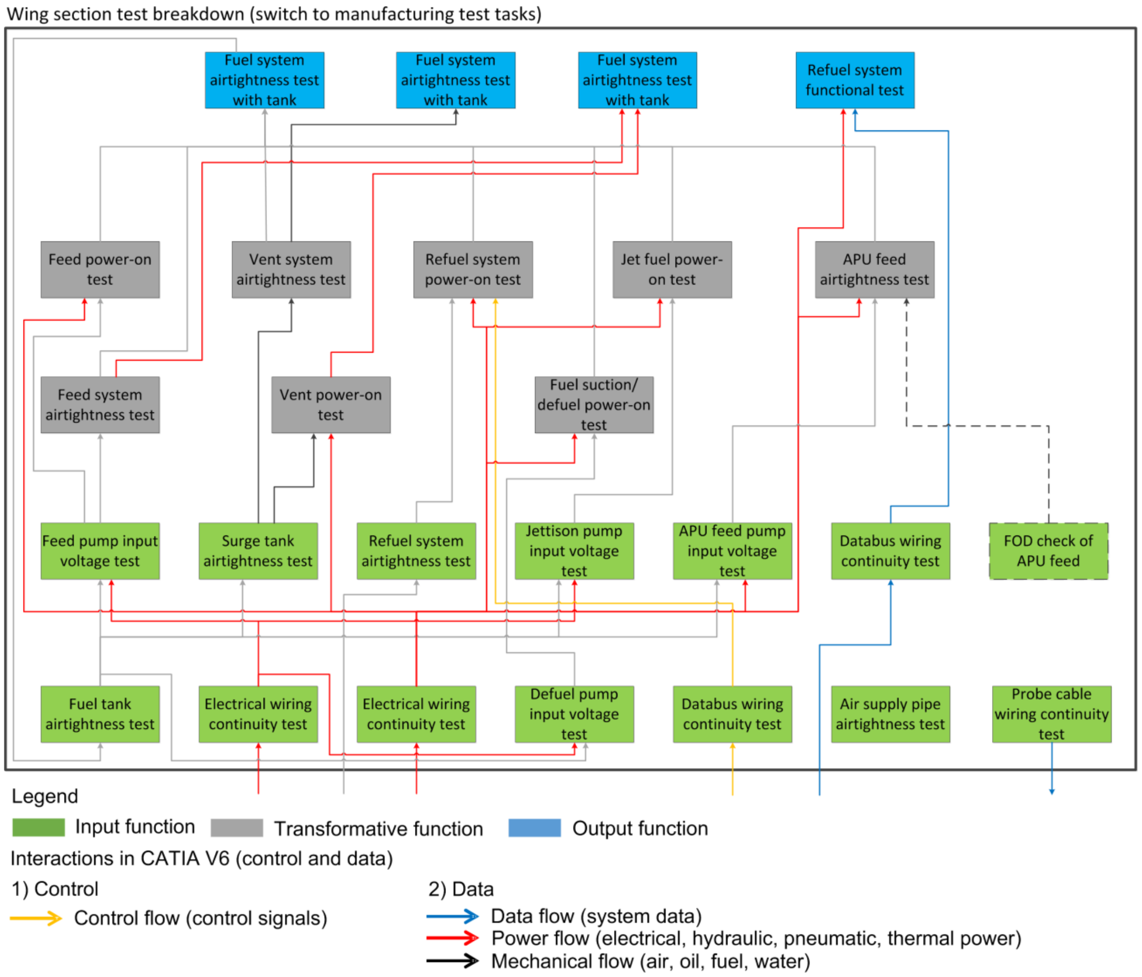


Figure 5-19 'Test' hierarchy of B777 wing assembly line

Once the 'test' hierarchy is built, the interactions in the 'test' hierarchy are checked by applying the method step 2-5 to produce a test breakdown structure. The main result includes:

- These test tasks are grouped following the general structure of the 'test' hierarchy from "input functions" tests, to "transformative function" tests and the final "output function" tests.
- Test tasks with same test names or similar test content are combined to arrange at the same time. For example, the three "fuel system airtightness tests", and two "electrical wiring continuity test" are combined as one test task respectively.
- The tests with multi-connection interactions are sorted based on the analysis of which is the priority integration for associated functions. There

are still detailed sequences can be decided in each group of tests. For example, the “fuel tank airtightness test” and “electrical wiring continuity test” should be arranged in priority with fuel sub-system airtightness tests and fuel pump voltage tests, as they are the basis for other “input function” tests.

- The tests associated with independent functions or having few interactions are arranged as flexible FNLT test tasks, such as the “probe cable wiring continuity test” and “air supply pipe airtightness test”. They should be done no later than the “transformative function” test.
- The “FOD check of APU feed” is kept for reference in the overall process

The sorted test breakdown structure is shown in figure 5-20.

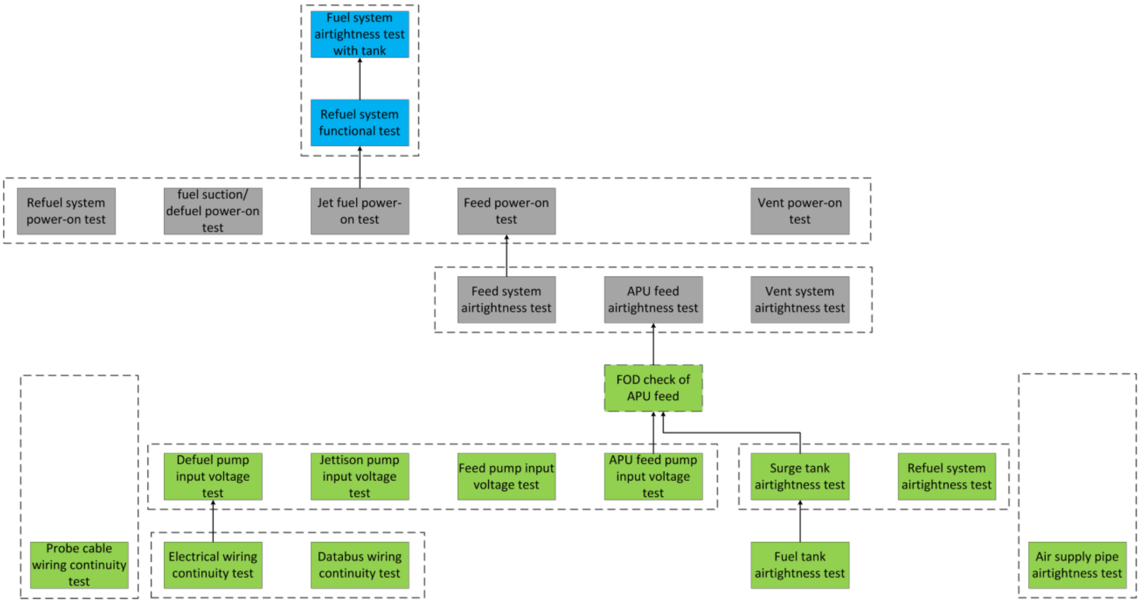
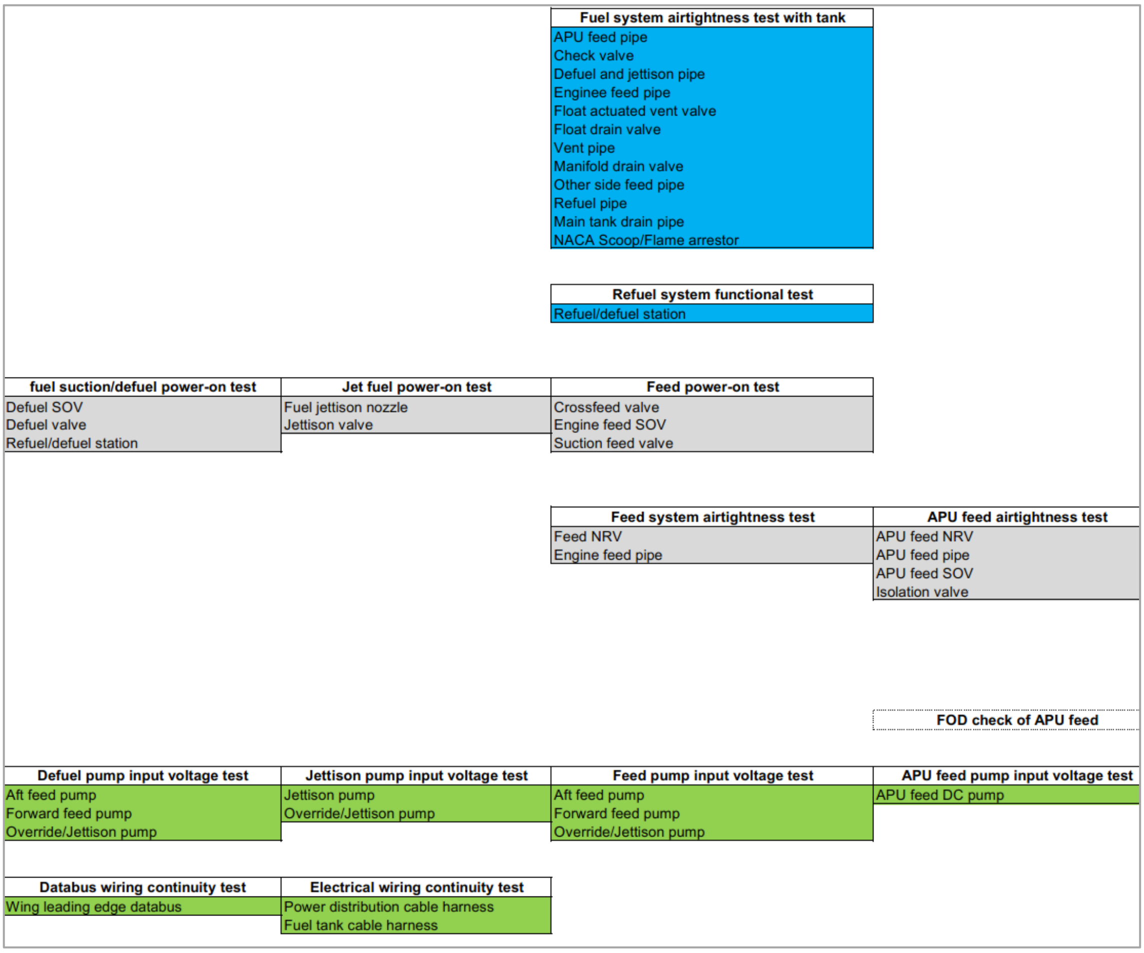


Figure 5-20 Sorted test breakdown structure of B777 wing assembly line

This test breakdown structure is then expanded to link the logical components through the functional-logical traceability information in the RFLP model. In the sequence result, some logical components such as the piping of fuel sub-systems are found appearing twice. This is due to one logical component may be required both from the functions at the sub-system level and the major system level. In the case of piping, they are traced to some basic functions of fuel system including fuel transferring and delivering. They are therefore required both at sub-system and major system level. The result of step 2 is partly shown in figure 5-21 in a bottom-up manner. The full sequence result of step 2 is provided in the Appendix C.4.1.



Fuel system airtightness test with tank
APU feed pipe
Check valve
Defuel and jettison pipe
Enginee feed pipe
Float actuated vent valve
Float drain valve
Vent pipe
Manifold drain valve
Other side feed pipe
Refuel pipe
Main tank drain pipe
NACA Scoop/Flame arrestor

Refuel system functional test
Refuel/defuel station

fuel suction/defuel power-on test
Defuel SOV
Defuel valve
Refuel/defuel station

Jet fuel power-on test
Fuel jettison nozzle
Jettison valve

Feed power-on test
Crossfeed valve
Engine feed SOV
Suction feed valve

Feed system airtightness test
Feed NRV
Engine feed pipe

APU feed airtightness test
APU feed NRV
APU feed pipe
APU feed SOV
Isolation valve

FOD check of APU feed

Defuel pump input voltage test
Aft feed pump
Forward feed pump
Override/Jettison pump

Jettison pump input voltage test
Jettison pump
Override/Jettison pump

Feed pump input voltage test
Aft feed pump
Forward feed pump
Override/Jettison pump

APU feed pump input voltage test
APU feed DC pump

Databus wiring continuity test
Wing leading edge databus

Electrical wiring continuity test
Power distribution cable harness
Fuel tank cable harness

Figure 5-21 Part of the B777 wing section systems test sequence associated with logical components

5.2.3 Step 3 implementation: B777 installation task allocation

In step 3, the logical components in the generated test breakdown structure are allocated to 3D physical models, which produce the initial feasible system integration sequence. These test related physical installations are FNLT installation tasks which means they are allowed to be finished earlier. This also leaves room for assembly line balancing in detailed assembly line design. The generated initial feasible integration sequence is partly shown in figure 5-22 (a) (a larger full version of figure 5-22 (a) is provided in Appendix C.4.2).

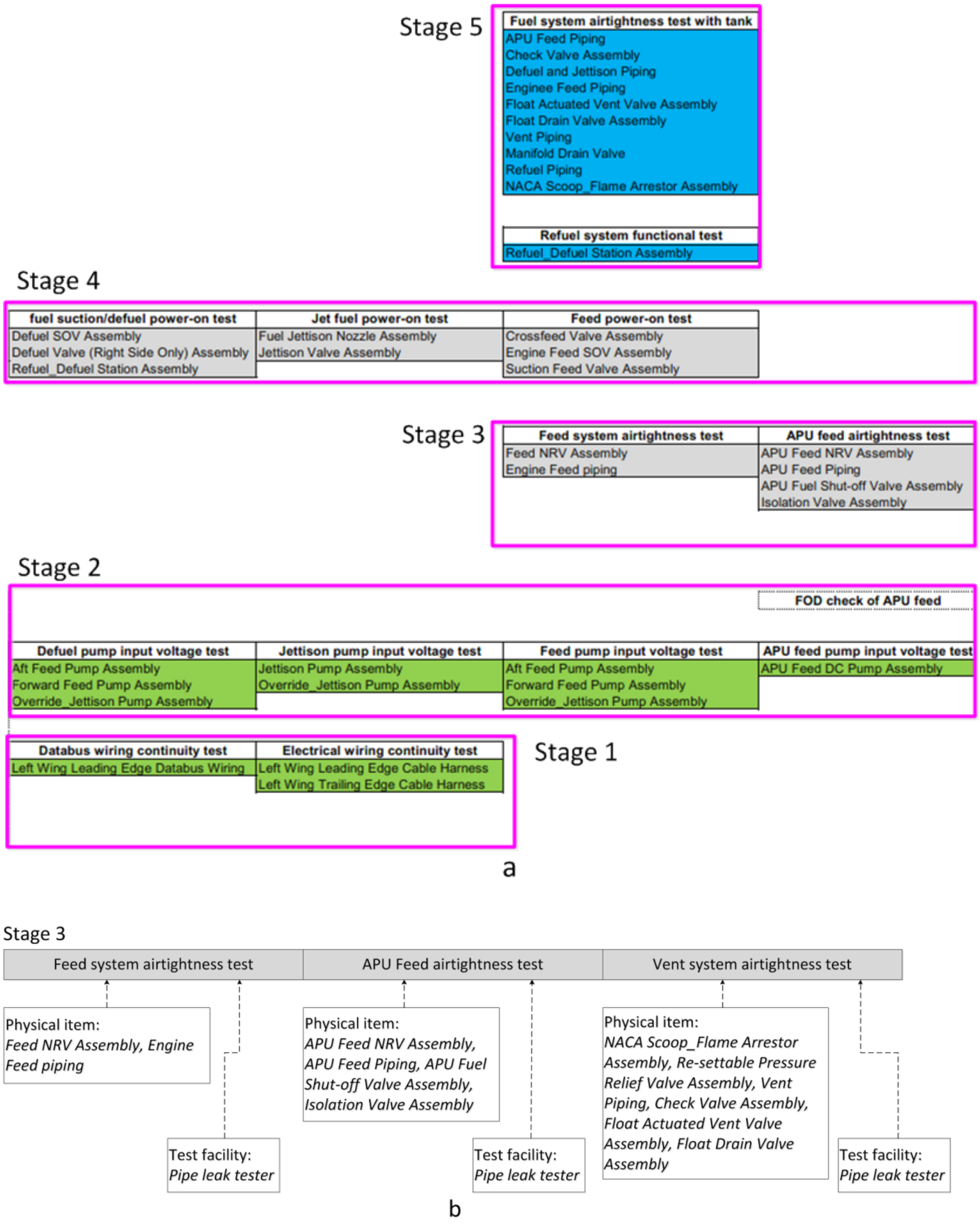


Figure 5-22 (a) Part of the initial feasible B777 wing section assembly integration sequence; (b) Detailed view of stage 3 (with physical items and test facility examples)

The sequence in figure 5-22 (a) shows that the overall integration process can be subdivided into five main stages:

- First in stage 1, fuel probes, electrical wiring and ECS air supply piping layout are finished followed by ECS pipe lines airtightness test and electrical continuity tests. The main fuel tanks airtightness test is also arranged at this beginning stage.
- After that, more installations and tests can be performed in stage 2. The integrations in stage 2 include the installation of several fuel sub-system components and equipment such as pipes, valves and pumps. Tests in stage 2 are mainly the input voltage test for the fuel pumps, and refuel system airtightness test. The surge tank is a more isolated area than other fuel tanks. According to the dependencies in the 'test' hierarchy, surge tanks have more interactions with the vent control. Thus, other fuel sub-system installation and test tasks are arranged earlier than the tasks in surge tank. Surge tank air tightness test is then finished at the end of stage 2.
- In stage 3, most of the fuel sub-systems are installed and finished with an air tightness test to ensure they are in good condition and ready for next stage sub-system function verification.
- In stage 4, after some additional installations of control valves, the fuel sub-systems are verified by several sub-system power-on tests. The tests of stage 4 ensures the installed systems are ready for next stage integration
- The main integration in stage 5 is the refuel system functional test and the overall fuel system airtightness with all the fuel tanks.

It is interesting to find in stage 5 (see figure C-20 in the Appendix), the fuel system functional test associates some physical installations that have already been installed at early stages. For example, the "fuel system airtightness test with tank" requires all the sub-systems piping, and they have been installed at early stages. Besides, the "refuel/defuel station" is installed in stage 4, and it is required for the "refuel system functional test" in stage 5. As discussed before in section 5.2.1.3, a logical component may link to different functions. If the function performing of sub-systems are almost the same as when they are integrated in a bigger system, the associated logical components and physical items will be traced more than one time. However, as all the installation tasks are treated as FNLT tasks, such situation will not lead to an infeasible system integration sequence.

The needs for test facilities at each stage can be generated by tracing the interactions between sub-systems. In the B777 case study, an air interaction from the assembly line indicates the need of a pipe leak test facility, and an electrical interaction will supported by the ground electrical power supplier. Figure 5-22 (b) presents the required physical installations and test facilities needed in stage 3.

5.2.4 Step 4 implementation: B777 test related physical conditions analysis

4-1. Zone partitioning

In step 4, the B777 port wing section is partitioned into four zones preliminarily as below and shown in figure 5-23.

- Zone 1: port wing leading edge
- Zone 2: port wing trailing edge
- Zone 3: port wing centre tank and dry bay
- Zone 4: port wing main tank and surge tank zone

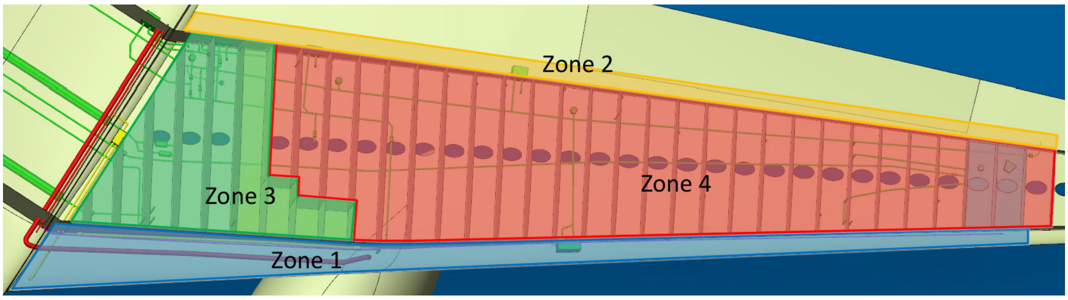


Figure 5-23 B777 wing section zone partitioning

4-2. Functional flow check

The continuous functional flows are examined in the four zones and listed in table 5-5.

Table 5-5 Functional flows in the four zones

	Zone 1	Zone 2	Zone 3	Zone 4
Control flow	Refuel/defuel control	N/A	N/A	N/A
Data flow	Refuelling data Probe data	Probe data	Probe data	Probe data
Power flow	AC electrical power DC electrical power	AC electrical power DC electrical power	AC electrical power DC electrical power	AC electrical power DC electrical power Air (pneumatic power)
Mechanical flow	Bleed air Ram air	Jettison fuel	Engine feed fuel Defuel fuel Refuelling fuel Surge tank fuel APU feed fuel Tank air	Engine feed fuel Defuel fuel Refuelling fuel Surge tank fuel Tank air

4-3. System break check

Then, the system breaks near the zone boundary are checked by these test tasks at each stage. This sub-step investigates the system interfaces needed for the verification tests to help improving the zone definitions in next sub-step. Table 5-6 shows the check results of the stage 1 tests. The complete check results are provided in the Appendix C.4.3.

Table 5-6 System break check result of stage 1 tests

Any system breaks near the structure or bay boundary for test blocking or connection?				
Test	Zone 1	Zone 2	Zone 3	Zone 4
Databus wiring continuity test	Yes, cable plugs	N/A	N/A	N/A
Electrical wiring continuity test	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs
Probe cable wiring continuity test	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs
Fuel tank airtightness test	N/A	N/A	Yes, structural connectors	Yes, structural connectors
Air supply pipe airtightness test	Yes, pipe ends and breaks at the wing root, and engine pipe connectors	N/A	N/A	N/A

4-4. Zone finalisation

The zone finalisation is finished by including the adjacent system breaks and components that are needed for the system tests. The added system components in each zone are listed in table 5-7.

Table 5-7 System components included in the improved zone

Zone	System components			
	Fuel system	Electrical system	ECS	Avionics system
Zone 1	N/A	Cable plugs at wing root Cable plugs to engine	Pipe breaks at wing root Pipe ends to engine	Cable plugs at wing root
Zone 2	N/A	Cable plugs at wing root	N/A	N/A
Zone 3	Pipe breaks at wing root	N/A	N/A	N/A
Zone 4	Pipe ends to engine Jettison nozzle Jettison valve	Cable plugs of jettison valve	N/A	N/A

4-5. Installation/uninstallation path check

In this sub-step, the accessibility of test related system components and test equipment are checked to find whether the initial sequence is still feasible. The analysis results of stage 1 are shown in table 5-8. The results of all the five stages are provided in the Appendix C.4.3.

Table 5-8 Test related accessibility path analysis results at stage 1

Can current test sequence satisfy aircraft system installation/uninstallation path?		
Stage	Test	Check result
1	Databus wiring continuity test	Yes, databus cable harnesses can be installed first in this zone before electrical cable harness. The wiring continuity test can be done in parallel.
1	Electrical wiring continuity test	Yes, electrical cable harness can be installed with tank cable. The wiring continuity test can be done in parallel.
1	Probe cable wiring continuity test	Yes, probe cable harness can be installed with electrical cable. The wiring continuity test can be done in parallel.
1	Fuel tank airtightness test	Yes. But testing fuel tank airtightness at this point means the tank structure is closed. System tests and related installations/uninstallations are accessed through access panels. The path space may not be sufficient. Need to be reviewed in later development stage once more system physical design information is available.
1	Air supply pipe airtightness test	Yes. There are no technical constraints at input test functional level for installation of air supply pipe. The installation and test can be used as work load balancing in later stage.

The results of the accessibility checking in stage 1 show that the initial sequence generally meets the accessibility requirements of tests. In the current sequence, the fuel tank airtightness is tested at the beginning. This means the fuel tank structures need to be closed first to perform the airtightness test, and the fuel tank walls and surfaces cannot be re-opened again for system installations. Almost all the fuel system and part of the electrical system components can only be installed through the wing tank access panels. The arrangement of fuel tank airtightness test thus has significant influence to the systems installed in the fuel tanks. The analysis results from other stages also indicate that the current sequence is flexible to be changed if more detailed design information is available. The changes of the current sequence may be caused by the accessibility problem and needs of more systems pre-equipping in the wing tanks. For instance, some fuel tank pipes and tank cable wirings can be installed and pre-equipped in the fuel tanks, only leaving the systems that are easily accessed installed after the tank structure is closed. However, as detailed 3D physical design information is released at later aircraft detailed design stage, it is not possible to analyse the sequence for accessibility. In spite of this uncertain factor, the current integration sequence in figure 5-22 (a) is still feasible for all the test requirements.

5.2.5 Summary of the B777 case study results

The second case study concentrates on the implementation of proposed method under an industry-like environment. By applying this strategy, the B777 case study is much more complicated than the first E-15 aircraft which includes specific requirements, functional, logical and physical design information. The generated assembly integration sequence provides more detailed sequences of four major systems. The B777 case study introduces more constraints from wing fuel tanks, thus making it closer to real implementation environment. The generated sequence has five integration stages which consist of system installation and test following the SE production verification principles. The air tightness test of fuel tanks is involved in the overall system integration sequence. This illustrates the strong physical integration characteristics of fuel system, which was introduced in the literature review (see figure 2-4). The initial sequence also indicates that the ECS and probe cable installations and tests are flexible tasks because they have few dependencies with other systems. Although the physical design information is not sufficient to support a more detailed sequence analysis when using method step 4, the generated sequence is feasible and reliable. The step 4 analysis also suggests the initial sequence to be reviewed once more design and assembly information is available. In general, the installations in the generated sequence are all treated as FNLT tasks, and there are several flexible integration tasks in the sequence. Thus it would be a good sequence basis for further assembly line balancing.

5.3 Research Validation

This research will use semi-structured interviews for data collection and analysis (Miles and Huberman, 1994). This is because an ideal situation for this research is to interview people who have both design and assembly experience. However, it is not possible to find a large number of people with such know-how and knowledge in the duration of study. Thus, the traditional feedback data collection methods, such as surveys and questionnaires are not available because of the small sampling. For example, it is not possible to simply draw the conclusion that 80% people of 30 participants agree that the method is feasible. Semi-structured interviews allow for more open questioning that allow respondents to express their own views based on their experience. At last, based on the validation methodology introduced in section 3.2.3, the semi-structured interview technique will be applied to collect data from a set of questions. The interviews will be analysed to identify "themes" extracting the key information that respondents gave.

5.3.1 Interview introduction

The research validation has been undertaken with five people from academia and industry using semi-structured interviews for research feedback and evaluation. A brief interviewees' profile are introduced in appendix D. This interview includes a twenty minutes presentation about the research, and then a number of pre-defined questions are given to the interviewee. These questions consist of two parts: two general questions and eight project questions. The general questions aims understand the background of interviewees, and their relevant knowledge of aircraft assembly. The project questions include topics in characteristics of complex systems, gaps in literature, method benefits and drawbacks, case study and industrial implementation. A complete interview question list is provided in Appendix D. According to Miles and Huberman (1994) qualitative interview data should be analysed using the coding technique, which is the organisation of raw data into conceptual categories. Each code can be a category or theme. This includes words, phrases, sentences or even whole paragraphs. The following sections will present the interview results by those identified themes.

5.3.2 Results

5.3.2.1 Definition of aircraft complex systems

Generally, all interviewees acknowledged the large number of components contribute much to the aircraft system complexity. Another aspect they realised is that aircraft systems are complex in the distributed locations as “they are often distributed around the airplane” (participant C). When people try to allocate the systems from design, they need to “get all these system tracing in many different structural part of the aircraft” (participant B). Two interviewees identified the complexity is mostly from avionics and airframe systems, as they stated that “Most of these modern functions are really from electronic systems” (participant B), and “Avionics looks complex to me. Airframe systems are complex as well. The hydraulic system is quite complex, as is the electrical power. But ECS is probably the most complex I am afraid in the airframe systems” (participant C). Participant D explains the system complexity from the integration and engineering process aspect. “In the integrated system architecture, it is complexity because of the large numbers of sub-systems and system interactions included in the modules”. Participant D emphasized that in the system integration design process, systems “become bigger very quickly”. Participant E concerns the complex system development difficulty of satisfying design requirements in assembly line environment as “the more requirements the aircraft have to meet, the more complicated an assembly process will be”. The main factors that were identified for the definition of complexity in aircraft systems were the large number of physical components, the physical distribution of the components and the integration of electronics and avionics components. These are well aligned with the challenges identified in the literature review.

5.3.2.2 System dependency information in current engineering data sources

Drawings and CAD models are the main engineering data sources for assembly integration design. All the interviewees pointed out that no system functional dependency information is included in 3D CAD models.

Participant E explained with an hydraulic system example, that “assembly planners with aircraft system knowledge “probably know where the hydraulics goes to in the aircraft bays, and probably they know which system goes to another system. But they don’t necessarily know the detailed functionality of a particular hydraulic, and they certainly won’t know the interactions between the hydraulic systems”.

As stated by participant A: “If I just see the physical system installed on the wing or in a CAD mock-up, I wouldn't directly know what the functions are between different components. So you will have to have some other functional diagrams to be able to see that. If you only have drawings or a digital mock-up, then understanding the functions or the function between systems is probably not enough.” The current assembly process planning therefore is paper-based process (participant B), and much relied on assembly planner’s experience to understand system functions (participant A).

Participant C indicated the drawback of current CAD engineering data source that “CAD models certainly help in terms of the physical location and the interactions between the various components, but the system architecture is a crucial thing to see how the functions that catalogued. I think they're absolutely vital, but not complete”.

In conclusion, the main challenges identified for systems dependency information were the lack of system functional dependency information in 3D CAD models and the difficulty for assembly planners to know the detailed functionality of systems.

5.3.2.3 Method evaluations

Participant A concluded that method is “mainly focusing on testing the systems for their functions during the assembly process, where the tests are linked to the function they are supposed to do”.

The participants evaluated the benefits of the proposed method include:

- Linking design and assembly with requirement traceability:
    - Participant A evaluated that “the traceability is very good. It links the information from the design side especially the system engineers, where the information they access to is mainly based on the design requirements and the design functions of the system to assembly planning aspects”.
    - Participant B stated that the method “makes links between the components that we assembled and the function they contributed. So it is able to make the link from the engineering functional view of the aircraft, down to the physical components that we installed in the assembly lines”.
    - Participant C said “I like the traceability both forward and rear traceability, making very explicit the requirements, the functions, the system architecture under testing”.
- Better integration sequence that reduce risks:
    - Participant B evaluated it as “a way to integrate things better for the functional test activities along the assembly sequence. It is about thinking in the sub-assembly sequence, and to know at what point you will really be able to make some functional tests”, thus “optimise better in the assembly sequence, increasing the feasibility and reducing risks. This is a key feature for a good industry system”.
    - Participant C highlighted the significant benefit of the method as “bringing integrating the manufacturing and assembly engineering in the design process. And that must help in terms of reducing conflicts in design. Clearly, the ordering of the sequencing, I think is important too, that should save time and avoid rework”.

  - Participant D stated that the proposed method builds a process to “help capturing requirements consistency issues earlier in the design process”. It reduces risks by “solving issues before everything goes into the production process”.
- Less aircraft systems knowledge and experience required and better understanding of design
  - Participant A found it is “a method to help with the process when you don't have the experience and the design is completely new”. By applying this method people “would be in a better position to layout the new assembly sequence where they don't have that experience yet on how it has been done in the past. So they could have the benefit of seeing why the design has these functions and the components contribute to these functions”.
  - As an assembly planner, participant E concluded that “the proposed method builds up an integrated system to help with sequence generation”. Thus, “less systems knowledge is required for assembly line engineering”.

The participants also pointed out the drawback of this method as follow:

- Not an optimisation based approach
  - Participant A stated the possible drawback as: method is “not an optimisation based sequence approach. It's an initial starting point design approach here”. But this participant further explained that “I am not sure that's a drawback, because you need to start somewhere. I suppose you have to show that you are making a good start”.
- Sequence relies much on correct interaction definition
  - Participant B noticed that prerequisite of this method as: “If the objectives are defined correctly, it is then able to further optimise the assembly line sequence by testing your finished product early enough, to decide the distribution of the test along the assembly sequence”.

5.3.2.4 Evaluation of case study results

The E-15 case study was presented to the interviewees. Generally, the main themes identified for the E-15 case study results were:

- Provide a baseline sequence for future work
    - Participant A acknowledged that at early design stages it is difficult to produce a feasible integration sequence due to limited system location information. The sequence generated in this case study shows by applying this method, “just some design information is ok” to generate a feasible sequence. In later development stage, “as you have more information, you would re-assess your assembly sequence” again.
    - Participant E evaluated the results from the assembly planner’s aspect. “The proposed method builds up pathways for design information to be delivered to manufacturing logically. Hence, the results generated follows the path of system integration, which would be a baseline for future optimizations”
- Ensure a proper sequence of systems integration tests.
    - Participant B examined the results from the SE aspect. This participant found the results make it is “able to test earlier and have more things in parallel” by taking equipment and installations into account in the sub-sequences.
    - Participant D agreed that the case study results are feasible because “the production tests are carefully structured” by applying the new method. This participant added that aircraft radar systems detection functional test and integrated avionic test are typical examples that should be tested in a proper sequence. The results fit well with those requirements.
- Lack of aircraft structure interaction
    - Participant C pointed out that “some of the avionics racks are obviously structural components, but the interactions to the both sides are important”. This participant thought “structure is a definite thing that needs to be looked at as a recommendation future work”.

5.3.2.5 Suitability of the proposed method in industry

The interviewees evaluated the suitability of this method by their industrial context, which can be concluded as following:

- ✓ Would be applied for a new product if this tool can be integrated with industry processes (participant A)
- ✓ Applicable in industrial practice but needs adapting to specified implementation environment (participant B)
- ✓ Particularly useful for aircraft safety analysis, especially when combining with ZSA tool (participant C)
- ✓ Would be applied to assembly planner's daily work if update of PLM systems and modelling tools can be achieved (participant E).

5.3.3 Validation summary

The validation study provided feedback on the research from an academic and industrial viewpoint. The interviewees all acknowledged that the modern advanced aircraft systems contribute much to the development difficulty, and the current engineering data sources are not well integrated for assembly process planning. The interviewees evaluated the proposed method and case study results based on their knowledge and background. They highlighted the benefits of the proposed method as: linking design and assembly with requirement traceability, better integration sequence that reduce risks, less aircraft systems knowledge and experience required, and better understanding of design. They also pointed out some drawbacks of this method that may limit the method implementation. The interviewees evaluated the E-15 case study results are feasible but have some limitations. However, the generated results will be a good baseline sequence as it ensuring the systems integration test properly. Finally, all the interviewees found the proposed method would be applied in their industrial context, and it has the potential to be implemented in aircraft safety engineering.

5.4 Chapter summary

This chapter describes the RFLP modelling and assembly sequence generation processes using two case studies. The results show that the proposed method is applicable for aircraft complex systems when using dependency information from aircraft functional design. Research validation is provided at the end of this chapter. Due to the limited numbers of the people that can provide feedback, and the need to give respondents the freedom to express their views from their own experience, a semi-structure interview technique is decided to apply in research validation.

6 DISCUSSION

This chapter discusses the research findings based on the research objectives.

6.1 Discussion of research objectives

There are six research objectives in this project (see section 1.4). The first two objectives are about the literature of advanced aircraft systems development and assembly integration methods. The third objective proposed the methodology of linking system design process and assembly process planning. Then, detailed modelling rules and expanded implementation of the method are developed for the fourth and fifth objectives respectively. The final objective has been applied by using two case studies. These research objectives are discussed in the following sub-sections.

6.1.1 Influence of aircraft complex systems on assembly integration

A comprehensive literature review has been undertaken, first on the relationship between complex systems design and assembly integration. It was found in the literature that most previous research on aircraft assembly uses aircraft assembly sequence of major structural sections as the baseline to carry on further work, ignoring the influence from aircraft systems (Caggiano, Marzano and Teti, 2016; Gómez et al., 2016; Mas et al., 2013; Menéndez et al., 2012; Scott, 1994). However, a modern advanced aircraft is complex both in its geometry and functions. Using only the assembly sequence of major structural sections as the baseline is not appropriate. The ASP methods found in literature are all based on physical connection information (Ben-Arieh and Kramer, 1994; De Fazio and Whitney, 1987; Homem de Mello and Sanderson, 1991; Pintzos et al., 2016; Wei, 2012a). Hence, they are not suitable for generating complex systems integration sequence such as a modern advanced aircraft. This is the gap found in literature.

To some extent, it is the characteristics of complex systems that limit the implementation scope of these ASP methods. The methods based on physical connections could be used in the very detailed sequence generation of sub-assemblies but not be used to define major integration stages. What is more, from a higher development view, the structural assembly is actually involved in the overall aircraft function integration process. If considering structure as part of the complex systems, structure could provide basic mechanical functions of connection, joining, supporting and attaching for structural and system components. To limit the research scope, in this research, the assembly integration process is considered to emerge from the aircraft functions that are closely connected to the aircraft systems. This approach helps to give a comprehensive understanding of the aircraft integration process, especially for the systems under integrated controlled architecture.

6.1.2 Implementation of SE principles for assembly sequence planning

SE principles and tools are widely used to solve the issues in complex system development, and products will benefit if SE is implemented properly. It is found in the literature that typical guidelines for aircraft system development only cover the implementation of SE in the design stage (Society of Automotive Engineers, 2010). Although there are some researchers who apply SE principles and tools in manufacturing, they mostly concentrate on building of the manufacturing systems for operations management rather than applying SE for aircraft integration at manufacturing stage (Milner, Volas and Sanders, 2013; Sage, 1996; Verbeek, 2013). In the literature, the acknowledgement that assembly line design is part of the product industrialisation process is a view from project management aspect (Mas et al., 2013). This is another gap found in the literature. From the SE view, aircraft assembly line design is part of the product introduction process, specifically in integration of design requirements and specifications to real production units. This understanding is of importance for linking the aircraft complex systems design and assembly process planning, as the function integration process at assembly stage is associated with the requirement decompositions through the design process. SE 'V' model clarifies the relationships between design and verification activities. The system integration sequence in an assembly line is now clearly that it is part of the requirements decomposition process: from requirements to design specifications, functional design information, and finally to the physical assembly information. In other words, if the activities and information in the ‘V’ model can be associated directly, it is possible to generate an assembly integration sequence towards requirements. The SE RFLP framework provides an opportunity to make this idea come true.

6.1.3 Integration of functional design into traditional physical engineering data source

This thesis has presented an assembly process design method for aircraft complex systems installation and test integration. The primary research objective has been the development of a method to integrate the systems engineering and assembly approaches that will help assembly process engineer understand system interferences and generate an initial feasible integration sequence. As presented in figure 4-7, in the concurrent engineering mode assembly process planning can pick up the engineering outputs of early aircraft design earlier to support generating an initial feasible sequence. To generate an assembly process, assembly process planning requires detailed product geometrical information, component connections and accessibility constraints. At early product development stages, aircraft systems assembly design only has general components layout, which is not sufficient to generate the assembly integration sequence. By applying SE principles for assembly integration, the functional information at early stages is sufficient for early assembly sequence generation. Such a sequence is an initial feasible sequence because it follows the path of system function introduction. The idea of applying SE on complex systems assembly sequence generation makes it is possible to have a reliable installation and test process with less potential risks than experience-based or major structural sections approaches. After several candidate proposals and tests, this object has finally been met through development of specialised models under the SE RFLP framework as new engineering data sources, which can be structurally extracted functional and physical information in later assembly process planning. This is further achieved by implementation of integrated CAD method within a uniform PLM system to management the associated requirements, functional, logical and physical models. The new developed RFLP modelling rules ensure the integration of functional and physical design information in CATIA V6 software implementation environment, and easily obtain the functional dependencies with 3D physical models in assembly process planning. This method therefore expands the implementation areas of RFLP models from design to assembly.

It should be emphasised that the proposed method aims to generate the installation and test sequence from the dependency information in the engineering data sources, rather than using traditional "structural sections sequence" and "structure to system" experience-based approaches, or using the physical connection based methods. By generating the installation and test precedence from the functional and physical information of engineering data sources, the proposed method has the advantages of better connection to design and requirements, clearer functional constraints in the sequence, and less personal experience required than the previous ASP methods. The proposed method answers the research hypothesis in section 1.2, that SE principles can be used to help assembly planners to better understand product design data and support generating more reliable installation and test processes.

6.1.4 Reusing models to support the assembly sequence planning

Reusing the RFLP models makes the design and manufacture use the same engineering data source in the concurrent engineering environment, which helps designer better fit in the assembly integration. Besides, the assembly planners would make reliable sequence decision making and provide feedback towards the RFLP models. Reusing the RFLP models is based on the idea that an assembly tree structure represents the function integration process. The system functions in such an assembly tree are in the form of functional tests, or known as main integration stage gates in this research. This means that these "functional nodes" in the assembly tree structure can be deployed and linked with installations and even test facilities. Models are reused through the dependency uncoupling process to form an assembly process: the functional models are adapted into an assembly structure consisting of functional test nodes, and the logical models are deployed from functional models in the ‘test’ hierarchy through traceability links, and finally the 3D physical models are deployed from logical models as installation tasks in the assembly structure. Specifically, by reusing the RFLP models and their embedded traceability information, the generated assembly tree inherits the constraints of product functions, which makes the installation tasks are very close to the test tasks if putting the assembly tree in a timeline. Hence, installations in this assembly tree structure are all FNLT tasks. If using the absolute constraint concept of ASP from the literature (Marian, 2003; Rashid, Hutabarat and Tiwari, 2012), the test tasks in such an assembly tree structure are treated as absolute constraint that their precedence cannot be changed. Their associated installation tasks are flexible to some extent since installations can be arranged earlier, or the associated installation tasks can be arranged in several sub-assemblies. This is another significant benefit of the method compared to other ASP methods. The FNLT installation tasks also build a good basis for later supply chain design by understanding the time limits in the sequence. However, on the negative side, as explained in section 5.2.1.3 and 5.2.3, a logical component may link to different functions, thus one physical component may link to several tests. For complex systems, too many installations with the same task names existing in the assembly tree structure will add additional work for sequence sorting, because the same physical components can be only installed once in an assembly process.

6.1.5 Opportunity for further design and assembly optimisation

The method was first developed only including the first three steps. After the early implementation of the three steps on the E-15 case study, it was seen that more benefits could be gained from this method by carrying out additional assembly analysis for initial sequence optimisation and having opportunities to send feedback to aircraft design. It was also realised that the research scope is limited in early product development stages. As detailed 3D physical models are not available at early development stages, assembly analysis methods such as DFA and liaison diagram are not suitable to be included in the overall method.

Therefore, the additional assembly analysis is limited to the analysis of physical installations that are required for a specified test, aiming to use available physical and functional information in the RFLP models. This information includes the early aircraft system layouts, structural design and external functions in the functional model from method step 1. This is a limitation on the implementation of this method. However, the general workflow of step 4 provides the opportunity to connect to product design. The proposed method then has the potential of implementing on later development stages if more detailed physical information is available in the engineering data sources. In that case, the step 4 is possible to expand the “test related physical conditions” analysis to more broad DFA accessibility analysis, and hence makes the proposed method covering the detailed product design and assembly process planning stage.

It would be argued that even with method step 4, this method is still not an optimisation based approach. Indeed, the proposed method focuses on the integration problem of complex systems in early assembly process planning. This area is an important stage with high development risks. Optimisation problem is not the priority objective of this method. By developing step 4, the reliable baseline result could link with later detailed development stages. This also allows the later assembly line balancing result better fit the test tasks which are considered to be absolute constraints in this research.

6.1.6 Discussion on the two case studies

As introduced in chapter 5, the two case studies are selected with different development aims for the method. If looking at the case studies from aircraft system characteristics, it is interesting to find more differences in the detailed processing sub-steps and general sequence results. The Cranfield E-15 business jet is equipped with next generation avionics under the integrated modular digital system architecture, while the B777 airliner is the federated digital system architecture. In spite of the significant difference in component quantity, there are more repeated functional-logical traceability links defined in the B777 case study. When applying method step 2-5, a large amount of interaction identification, classification, removing and re-sorting work have to be taken in consequence. As explained in section 5.2.2, it is because one system component may be required both from the functions at the sub-systems level and the major system level. This situation is more common in airframe systems under the federated controlled system architecture, since in airframe system the functions performed are exactly the same at sub-system level and major system level. For example, the function of a cross-feed valve is exactly the same in engine feed sub-system and fuel system. The functions and logic control of airframe systems are distributed, while the logic control of avionics system is integrated in the central control computer. Thus, the E-15 case study has less repeated functional-logical traceability definitions and less re-sorting work in assembly sequence generation. In the two case studies, all the interactions are defined manually in CATIA V6. It is difficult to define so many repeated traceability links in RFLP modelling, and manually extract and pick up information from models in assembly sequence generation.

The two case studies results preliminarily indicate that the proposed method could be applied for industrial implementation. 3D physical models and PLM system have been widely used in aircraft industry for quite a long time. Requirement engineering and aircraft functional design are current practice in industry. This method is based on the RFLP framework, involving the proposed method into an industrial environment needs to expand current 3D physical models to RFLP models, and thus further includes and integrates the requirement engineering and functional design. Besides, as some ideas in developing the method are from existing industrial practice tools like the ZSA and SE ‘V’ model, this method is supposed to fit into the existing aircraft safety engineering and other SE practice workflows.

This thesis has presented a new assembly integration design method for aircraft complex systems installation and test. The work to date has proved the possibility of generating initial feasible sequence by using RFLP models as engineering data sources.

6.2 Future work

There are several possible areas of future work have been identified including:

- Testing the method in a more complicated case study that includes more structural interactions to investigate the potential to scale up to industrial application.
- Creating templates to allow fast picking of pre-defined interactions in software environment to improve the RFLP modelling efficiency
- Combining with the proposed method with RFLP that ensuring the RFLP model-based ZSA implementation

A long-term plan of future work includes:

- Simplifying the steps for functional and logical modelling
- Automatic sorting and fast picking the RFLP to assembly traceability information
- Expanding the proposed method to later aircraft development stages including preliminary design and detailed design stage
- Practicing in industry assembly project

7 CONCLUSION

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 personal experience and knowledge. 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 main novelty in this research can then be concluded as the development of a structured approach for early stage assembly process planning that combines aircraft systems design data with the use of integrated SE to ensure that system production verification requirements are considered in the system design and process planning. By applying this method, engineering data sources are integrated with requirement traceability information, which guarantees the requirements consistency in later assembly planning. On the other hand, assembly planners have opportunities to provide feedback to design based on the traceable RFLP models. According to the validations from semi-structure interviews, this method has the major benefits of linking design and assembly with requirement traceability, better integration sequence that reduce risks, less aircraft systems knowledge and experience required, and better understanding of product design. Thus, 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 research is tested on two case studies with different system control architecture. The results show that:

- The proposed method can produce a feasible assembly integration sequence.
- 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 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.
- Different aircraft systems and modelling interactions can be considered to give a multidisciplinary solution rather than looking at one system or structural sections only.
- The assembly sequence follows the integration path of aircraft system functions rather than only generating from 3D CAD physical connection information.
- Potential risks of traditional experience-based approach are avoided, that system functional issues at later flight test stage may lead to re-installations and re-tests.

It is suggested that the RFLP modelling efficiency could be improved by creating templates to allow fast picking of pre-defined interactions rather than inputting all the different interaction information manually. In addition, although the aircraft structure is out the scope of this research, if considering aircraft structure 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. At last, this method is recommended to combine with aircraft safety analysis to integrate design requirements and product functions in model-based ZSA.

REFERENCES

A. Delchambre (ed.) (1996) *CAD Method for Industrial Assembly : Concurrent Design of Products, Equipment and Control Systems*. Chichester: John Wiley & Sons, Ltd.

Aero Icarus (2017) *Airbus A380.*, *AINONLINE* Available at: https://www.ainonline.com/aviation-news/air-transport/2017-08-21/demand-surges-hajj-flights-southeast-asia (Accessed: 6 October 2018).

Air Accidents Investigation Branch (2009) *Report on the accident to Boeing 777-222, registration N786UA at London Heathrow Airport on 26 February 2007*.

Airbus (2014) *Final Assembly and Tests*. Available at: http://www.airbus.com/company/aircraft-manufacture/how-is-an-aircraft-built/final-assembly-and-tests/ (Accessed: 19 February 2016).

Akao, Y. (1988) *Quality Function Deployment: Integrating Customer Requirements into Product Design*.1st ed. Portland, OR: Productivity Press.

All Nippon Airways (2011) *All Nippon Airways Boeing 787-8*. Available at: https://commons.wikimedia.org/wiki/File:All_Nippon_Airways_Boeing_787-8_Dreamliner_JA801A_OKJ.jpg (Accessed: 28 May 2016).

Altfeld, H.-H. (2010) *Commercial Aircraft Projects: Managing the Development of Highly Complex Products*.1st ed. London: Routledge.

Andre, P. and Sorito, R. (2002) ‘Product Manufacturing Information (PMI) in 3D models: a basis for collaborative engineering in Product Creation Process (PCP)’, *Proceedings 14th European Simulation Symposium*.

ANSI/EIA (2003) *EIA Standard ANSI/EIA-632-2003 Processes for Engineering a System* ELECTRONIC INDUSTRIES ALLIANCE,

Ashford, R. (2004) ‘Verification and validation of the F/A-22 raptor environmental control system/thermal management system software’, *SAE Technical Papers*, (724) Ashmead, G.B. (1956) *Aircraft production methods*.1st editio. Philadelphia: Chilton Company.

Baudin, M. (2002) *Lean Assembly : The Nuts and Bolts of Making Assembly Operations Flow*. New York: Productivity Press.

Baughey, K. (2011) 'Functional and Logical Structures: A Systems Engineering Approach', *SAE Technical Papers*.

Ben-Arieh, D. and Kramer, B. (1994) Computer-aided Process Planning for Assembly: Generation of Assembly Operations Sequence *International Journal of Production Research*.

Bile, Y., Riaz, A., Guenov, M.D. and Molina-Cristobal, A. (2018) 'Towards Automating the Sizing Process in Conceptual (Airframe) Systems Architecting', *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. Reston, Virginia: American Institute of Aeronautics and Astronautics, pp. 1–24.

Bing, C., Jun, J., Shan, L. and Baohai, W. (2009) 'Single Source of Product Data Technology in Aero Engine Design and Manufacture Collaboration', *2009 Second International Conference on Intelligent Computation Technology and Automation*, , pp. 430–433.

Boeing Commercial Airplanes (2015) *Boeing 777-200LR/-300ER/-Freighter Airplane characteristics for airport planning*.

Boothroyd, G., Dewhurst, P. and Knight, W.A. (2011) *Product Design for Manufacture and Assembly*.3rd ed. Boca Raton: CRC Press, Taylor & Francis Group.

Boschian, V., Fanti, M.P. and Ukovich, W. (2012) *A PLM approach for services in transportation system management*. IFAC.

Bouchereau, V. and Rowlands, H. (2000) 'Methods and techniques to help quality function deployment (QFD)', *Benchmarking: An International Journal*, 7(1), pp. 8–20.

British Airways (1978) *Boeing 747 schematics and locations manual*. London: British Airways.

Brown, P.G. (1991) 'QFD: Echoing the Voice of the Customer', *AT&T Technical Journal*, 70(2), pp. 18–32.

Browning, T.R. (2001) 'Applying the design structure matrix to system decomposition and integration problems: A review and new directions', *IEEE Transactions on Engineering Management*, 48(3), pp. 292–306.

Burge, S. (2010) Systems Engineering: Using Systems Thinking to design better aerospace systems. *Encyclopedia of Aerospace Engineering*. p., pp. 1–24.

Burge, S. (2011) *The Systems Engineering Tool Box*. Available at: https://www.burgehugheswalsh.co.uk/Uploaded/1/Documents/N2-Analysis-Tool-Draft.pdf (Accessed: 2 June 2019).

Caggiano, A., Marzano, A. and Teti, R. (2016) 'Resource Efficient Configuration of an Aircraft Assembly Line', *Procedia CIRP*, 41 Elsevier B.V., pp. 236–241.

Caldwell, R.E. and Merdgen, D.B. (1991) 'Zonal analysis: the final step in system safety assessment (of aircraft)', *Annual Reliability and Maintainability Symposium. 1991 Proceedings*, , pp. 277–279.

Chen, Z. and Fielding, J.P. (2018) 'A zonal safety analysis methodology for preliminary aircraft systems and structural design', *Aeronautical Journal*, 122(1255), pp. 1330–1351.

Chiesa, S., Corpino, S., Fioriti, M., Rougier, A. and Viola, N. (2013) 'Zonal safety analysis in aircraft conceptual design: Application to SAvE aircraft', *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 227(4), pp. 714–733.

Collins Dictionaries (2017) *Assembly definition and meaning*., *Online Dictionary* Available at: https://en.oxforddictionaries.com/definition/assembly (Accessed: 20 August 2017).

Collinson, R.P.G. (2011) *Introduction to Avionics Systems*. Dordrecht: Springer Netherlands.

Cranfield University (2015a) *The Multipurpose Air Freighter F-14 Hermes Design Report (unpublished)*. Bedford.

Cranfield University (2015b) *Executive Summary of E-15 Peregrine Advanced Technology Business Jet (unpublished)*. Bedford.

Dale, B., Boaden, R., Wilcox, M. and McQuater, R. (1998) 'The use of quality management techniques and tools: an examination of some key issues', *International Journal of Technology Management*, 16(4/5/6), p. 305.

Dassault Systèmes (2009) *CATIA V5R20 Help Documentation*., *Online* Available at: http://catiadoc.free.fr/online/CATIAfr_C2/pfdugCATIAfrs.htm (Accessed: 16 September 2017).

Dassault Systèmes (2011) *V6 for Academia Discovery Workshop (unpublished keynotes)*.

Delligatti, L. (2013) *SysML Distilled: A Brief Guide to the Systems Modeling Language*.First. Addison Wesley.

Deuter, A. and Rizzo, S. (2016) 'A Critical View on PLM/ALM Convergence in Practice and Research', *Procedia Technology*, 26 The Author(s), pp. 405–412.

Doumbia, F., Laurent, O., Atger, D. and Robach, C. (2009) 'Using the Multiple-Clue approach for system testing on AIRBUS FAL (Final Assembly Line)', *2009 International Test Conference*. IEEE, pp. 1–9.

Drysdale, A.T. (2010) Safety and Integrity in Vehicle Systems. *Encyclopedia of Aerospace Engineering*. p., pp. 1–10.

Eppinger, S.D., Browning, T.R., Eppinger, S.D. and Browning, T.R. (2012) *Design structure matrix methods and applications*.1st ed. Cambridge, Massachusetts: The MIT Press.

European Aviation Safety Agency (2007) *Certification Specifications for Large Aeroplanes CS-25*.

Fanjiang, G., Grossman, J.H., Compton, W.D. and Reid, P.P. (2005) *Building a Better Delivery System: A New Engineering/Health Care Partnership*. Washington DC: National Academies Press.

De Fazio, T.L. and Whitney, D.E. (1987) ‘Simplified Generation of All Mechanical Assembly Sequences’, *IEEE Journal on Robotics and Automation*, 3(6), pp. 640–658.

Ficalora, J.P. and Cohen, L. (2009) *Quality Function Deployment and Six Sigma: A QFD Handbook*.2nd editio. Prentice Hall.

Frankenberger, E. (2007) ‘Concurrent Design and Realization of Aircraft Production Flow Lines – Process Challenges and Successful’, *International Conference on Engineering Design ICED’ 07 Paris*. Paris, pp. 1–11.

Friedenthal, S., Moore, A. and Steiner, R. (2009) OMG Systems Modeling Language Tutorial *INCOSE*.

Fritz, K., Kurz, N., Peterson, E. and Buese, R. (2013) ‘Dependencies Between Development (ARP4754A) and Production (Part 21, Subpart G) of Safety-Critical Avionics Equipment’, *SAE International Journal of Aerospace*, 6(2), pp. 2013-01–2122.

Gausemeier, J. and Moehringer, S. (2003) ‘New Guideline VDI 2206 – A Flexible Procedure Model for Specific Requirements to the Design of Mechatronic Systems’, *International Conference on Engineering Design Iced 03 Stockholm*, , p. 10.

Gertler, J. (2018) *F - 35 Joint Strike Fighter (JSF) Program*. Available at: www.crs.gov (Accessed: 28 November 2018).

Giachetti, R. (2016) ‘*Systems Engineering Thesis Research Methods*’, , pp. 1–6.

Gómez, A., Ríos, J., Mas, F. and Vizán, A. (2016) ‘Method and software application to assist in the conceptual design of aircraft final assembly lines’, *Journal of Manufacturing Systems*, 40 The Society of Manufacturing Engineers, pp. 37–53.

Guenov, M., Molina-Cristobal, A., Voloshin, V., Riaz, A., van Heerden, A.S., Sharma, S., Cuiller, C. and Giese, T. (2016) ‘Aircraft Systems Architecting - a Functional-Logical Domain Perspective’, *16th AIAA Aviation Technology, Integration, and Operations Conference*. Reston, Virginia: American Institute of Aeronautics and Astronautics, p. 3143.

Halfmann, N., Krause, D. and Umlauft, S. (2010) ‘Assembly concepts for aircraft cabin installation’, *Proceedings of the ASME 2010 10th Biennial Conference on Engineering Systems Design and Analysis*. ASME, pp. 1–7.

Harbottle, T. (2001) *Aging Transport Systems Rulemaking Advisory Committee Task 3 Final Report*.

Hasson, J. and Crotty, D. (1997) ‘Boeing’s safety assessment processes for commercial airplane designs’, *16th DASC. AIAA/IEEE Digital Avionics Systems Conference. Reflections to the Future. Proceedings*. IEEE, Vol.1, pp. 4.4-1–7.

Hemmaplardh, K.P., Milburn, K.M., Matthews, T.W., Chang, K.K. and Donaty, L.S. (2009) ‘Role of Power Distribution System Tests in Final Assembly of a Military Derivative Airplane’, *SAE International Journal of Aerospace*, 3(1), pp. 10–15.

Herzog, J. (2011) *Lufthansa Airbus A320-211*. Available at: https://en.wikipedia.org/wiki/File:Lufthansa_Airbus_A320-211_D-AIQT_01.jpg (Accessed: 5 July 2016).

Holley, V., Yannou, B. and Jankovic, M. (2010) ‘Towards the Prediction of Multiphysic Interactions Using MDM and QFD Matrices’, *Proceedings of DESIGN 2010, the 11th International Design Conference*., pp. 1109–1118.

Homem de Mello, L.S. and Sanderson, A.C. (1991) ‘A Correct and Complete Algorithm for the Generation of Mechanical Assembly Sequences’, *IEEE Transactions on Robotics and Automation*, 7(2), pp. 228–240.

Huang, J., Li, Y., Chu, X. and Chu, D. (2015) ‘An integrated top-down design process evaluation approach of complex products and systems based on hierarchical design structure matrix’, *International Journal of Computer*

Integrated Manufacturing, 28(10), pp. 1015–1029.

Hull, E., Jackson, K. and Dick, J. (2013) *Requirements Engineering*.3rd ed. London: Springer London.

INCOSE (2015) *Systems Engineering Handbook : A Guide for System Life Cycle Processes and Activities*.4th ed.Walden, D. D., Roedler, G. J., Forsberg, K., Hamelin, R. D. and Shortell, T. M. (eds.) Hoboken, New Jersey: Wiley.

ISO/IEC/IEEE (2015) *International Standard ISO/IEC/IEEE 15288-2015 Systems and software engineering - System life cycle processes* ISO/IEC/IEEE,

Jefferson, T.G., Benardos, P. and Ratchev, S. (2015) 'Reconfigurable Assembly System Design Methodology: A Wing Assembly Case Study', *SAE Int. J. Mater. Manf.*, 9(1), pp. 31–48.

Jia, G.Z. and Bai, M. (2011) 'An approach for manufacturing strategy development based on fuzzy-QFD', *Computers and Industrial Engineering*, 60(3), pp. 445–454.

Johnson, M. (1993) 'Boeing 777 Airplane Information Management System - Philosophy and Displays', *Advanced avionics on the Airbus A330/A340 and the Boeing-777 aircraft conference proceedings*. London, UK: The Royal Aeronautical Society.

Jones, J. and Hazlehurst, L. (2003) 'Factory of the Future', *AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years*, (October 2002)

Jones, R.E. and Wilson, R.H. (1996) '*A Survey of Constraints in Automated Assembly Planning*', 2(April), pp. 1525–1532 vol.2.

Jones, R.E., Wilson, R.H. and Caton, T.L. (1998) 'On Constraints in Assembly Planning', *IEEE Transactions on Robotics and Automation*, 14(6), pp. 849–863.

Judt, D., Forster, K., Lockett, H., Lawson, C. and Webb, P. (2016) 'Aircraft Wing Build Philosophy Change through System Pre-Equipping of Major Components', *SAE International Journal of Aerospace*, 9(1), pp. 2016-01–2120.

Kathawala, Y. and Motwani, J. (1994) ‘Implementing Quality Function Deployment’, *The TQM Magazine*, 6(6), pp. 31–37.

King, B. (1989) *Better Designs in Half the Time: Implementing QFD Quality Function Deployment in America*.3rd editio. GOAL/QPC.

Kleiner, S. and Kramer, C. (2013) ‘Model Based Design with Systems Engineering Based on RFLP Using V6’, in *23rd CIRP Design Conference*. , pp. 93–102.

Ko, J., Nazarian, E., Wang, H. and Abell, J. (2013) ‘An assembly decomposition model for subassembly planning considering imperfect inspection to reduce assembly defect rates’, *Journal of Manufacturing Systems*, 32(3) The Society of Manufacturing Engineers, pp. 412–416.

Kossiakoff, A., Sweet, N.W., Samuel, J.S. and Biemer, M.S. (2011) *Systems Engineering Principles and Practice*.2nd ed.Sage, P. A. (ed.) New Jersey: John Wiley & Sons, Inc.

Langton, R., Clark, C., Hewitt, M. and Richards, L. (2009) *Aircraft Fuel Systems*. Chichester, UK: John Wiley& Sons.

Li, J.S. (2013) ‘Continuous Improvement at Toyota Manufacturing Plant: Applications of Production Systems Engineering Methods’, *International Journal of Production Research*, 51(23–24), pp. 7235–7249.

Li, T. and Lockett, H. (2017) ‘An Investigation into the Interrelationship between Aircraft Systems and Final Assembly Process Design’, *Procedia CIRP*, 60 The Author(s), pp. 62–67.

Linzey, W.G. (2006) *Development of an Electrical Wire Interconnect System Risk Assessment Tool*.

Liu, H., Tian, Y., Gao, Y., Bai, J. and Zheng, J. (2015) ‘System of systems oriented flight vehicle conceptual design: Perspectives and progresses’, *Chinese Journal of Aeronautics*, 28(3) Chinese Society of Aeronautics and Astronautics, pp. 617–635.

Liu, H.T. (2009) ‘The extension of fuzzy QFD: From product planning to part deployment’, *Expert Systems with Applications*, 36(8), pp. 11131–11144.

Lockett, H., Fletcher, S. and Luquet, N. (2014) ‘Applying Design for Assembly Principles in Computer Aided Design to Make Small Changes that Improve the Efficiency of Manual Aircraft Systems Installations’, *SAE International Journal of Aerospace*, 7(2), pp. 284–291.

Lockett Martin (2004) Raptor Production in Marietta, *Code One*, 19(2), pp. 2–9.

Lockheed Martin (2006) *B-24 Liberator.*, *Air Freshener* Available at: https://airfreshener.club/quotes/b-liberator-squadrons-24.html (Accessed: 3 December 2015).

Lufthansa Technical Training GmbH (2013) *Boeing 777 Training Manual - ATA Quick Reference General*.

Madni, A. and Purohit, S. (2019) ‘Economic Analysis of Model-Based Systems Engineering’, *Systems*, 7(1), p. 12.

Marian, R.M. (2003) *Optimisation of Assembly Sequences Using Genetic Algorithms*. University of South Australia.

Mas, F., Arista, R., Oliva, M., Hiebert, B., Gilkerson, I. and Rios, J. (2015) ‘A Review of PLM Impact on US and EU Aerospace Industry’, *Procedia Engineering*, 132 Elsevier B.V., pp. 1053–1060.

Mas, F., Menendez, J.L., Oliva, M., Rios, J., Gomez, A. and Olmos, V. (2014) ‘IDMU as the collaborative engineering engine: Research experiences in airbus’, *2014 International Conference on Engineering, Technology and Innovation: Engineering Responsible Innovation in Products and Services, ICE 2014*, (June 2014)

Mas, F., Ríos, J., Menéndez, J.L. and Gómez, A. (2013) ‘A process-oriented approach to modeling the conceptual design of aircraft assembly lines’, *The International Journal of Advanced Manufacturing Technology*, 67(1–4), pp. 771–784.

McWha, J. (1993) ‘777 System Overview’, *Advanced Avionics on the Airbus A330/A340 and the Boeing-777 Aircraft Conference Proceedings*. London, UK: The Royal Aeronautical Society.

Menéndez, J.L., Mas, F., Serván, J. and Ríos, J. (2012) ‘Virtual verification of the AIRBUS A400M final assembly line industrialization’, *AIP Conference Proceedings*, 1431(September), pp. 641–648.

Messaadia, M., Belkadi, F., Eynard, B. and Sahraoui, A.E.K. (2012) *System engineering and PLM as an integrated approach for industry collaboration management*. IFAC.

Miles, M.B. and Huberman, A.M. (1994) *Qualitative data analysis: an expanded sourcebook*.2nd ed. London, UK: Thousand Oaks.

Milner, T., Volas, M. and Sanders, A. (2013) ‘Systems Engineering Methodology for Linking Requirements to Design Complexity and Manufacturing Trade Space Constraints’, *Procedia Computer Science*, 16, pp. 947–956.

Mishra, D.K., Sekhari, A., Henry, S. and Ouzrout, Y. (2017) ‘Data Model in PLM System to Support Product Traceability’, in Ríos, J., Bernard, A., Bouras, A. and Foufou, S. (eds.) *Product Lifecycle Management and the Industry of the Future*. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing, pp. 612–622.

Moir, I. and Seabridge, A. (2008) *Aircraft systems: Mechanical, electrical, and avionics subsystems integration*.3rd ed. Chichester: John Wiley & Sons.

Moir, I. and Seabridge, A. (2010) ‘Vehicle Systems Management’, *Encyclopedia of Aerospace Engineering*, , pp. 1–16.

Moir, I. and Seabridge, A. (2013) *Design and Development of Aircraft Systems*.2nd ed. Chichester: John Wiley & Sons.

Moir, I., Seabridge, A. and Jukes, M. (2006) *Military avionics systems*. Hoboken, NJ: John Wiley & Sons Ltd.

Moir, I., Seabridge, A. and Jukes, M. (2013) *Civil Avionis Systems*.2nd editio.

Chichester, West Sussex: John Wiley & Sons, Ltd.

Moubachir, Y. and Bouami, D. (2015) ‘A new approach for the transition between QFD phases’, *Procedia CIRP*, 26 Elsevier B.V., pp. 82–86.

NASA (2007) *NASA/SP-2007-6105 Rev 1: Systems Engineering Handbook*.Rev 1. Washington DC: NASA Center for AeroSpace Information.

New, C.C. (1977) *Managing the Manufacture of Complex Products : Coordinating Multicomponent Assembly*.1st ed. London: Business Books.

Ortegón, J., Mas, F., Gomez-Parra, A. and Marcos, M. (2017) ‘Virtual improvement of a historical aircraft assembly line’, *Procedia Manufacturing*, 13 Elsevier B.V., pp. 1312–1319.

Otto, K. and Wood, K. (2001) *Product Design : Techniques in Reverse Engineering and New Product Development*.1st ed.Curless, L. (ed.) New Jersey: Prentice Hall.

Oxford Online Dictionary (2019) *Test Meaning in Oxford Dictionary*. Available at: https://www.lexico.com/en/definition/test (Accessed: 20 January 2019).

Pallett, E.H.J. and Coyle, S. (1993) *Automatic Flight Control*.Fourth edi. Cambridge, MA: Blackwell Science.

Pardessus, T. (2004) ‘Concurrent Engineering Development and Practies For Aircraft Design At Airbus’, *24Th International Congress of the Aeronautical Sciences*., p. 9.

PAT Research (2018) *Top 19 Product Lifecycle Management*., *https://www.predictiveanalyticstoday.com/top-product-lifecycle-management-plm-software/* Available at: https://www.predictiveanalyticstoday.com/top-product-lifecycle-management-plm-software/ (Accessed: 10 March 2019).

Pingstone, A. (2008) *RAF Typhoon F2*. Available at: https://en.wikipedia.org/wiki/File:Typhoon_f2_zj910_arp.jpg (Accessed: 24 January 2017).

Pintzos, G., Triantafyllou, C., Papakostas, N., Mourtzis, D. and Chryssolouris, G.

(2016) ‘Assembly Precedence Diagram Generation Through Assembly Tiers Determination’, *International Journal of Computer Integrated Manufacturing*, 29(10), pp. 1045–1057.

Plankl, H. (2015) ‘Ground Test Facilities and Integration Concepts for Combat Air Systems at Airbus Defence and Space’, *SAE International Journal of Aerospace*

Pottenger, S. (1993) ‘Boeing 777 629 Data Bus - Principles, Development and Application’, *Advanced Avionics on the Airbus A330/A340 and the Boeing-777 Aircraft Conference Proceedings*. London, UK: The Royal Aeronautical Society.

Prasad, B. (2000) ‘A concurrent function deployment technique for a workgroup-based engineering design process’, *Journal of Engineering Design*, 11(2), pp. 103–119.

Rashid, M.F.F., Hutabarat, W. and Tiwari, A. (2012) ‘A Review on Assembly Sequence Planning and Assembly Line Balancing Optimisation Using Soft Computing Approaches’, *International Journal of Advanced Manufacturing Technology*, 59(1–4), pp. 335–349.

Rechtin, E. and Maier, M. (2000) *The Art of Systems Architecting*.2nd editio. Boca Raton, FL: CRC Press, Systems Engineering.

Rekiek, B. and Delchambre, A. (2006) *Assembly Line Design: The Balancing of Mixed-Model Hybrid Assembly Lines with Genetic Algorithms*.1st ed. London: Springer.

ReVelle, J.B., Moran, J.W. and Cox, C.A. (1998) *The QFD Handbook*.1st ed. New York: John Wiley & Sons, Inc.

Ríos, J., Mas, F. and Menéndez, J.L. (2012a) ‘A Review of the A400m Final Assembly Line Balancing Methodology’, *AIP Conference Proceedings*, 1431(1), pp. 601–608.

Ríos, J., Mas, F. and Menéndez, J.L. (2012b) ‘Aircraft Final Assembly Line Balancing and Workload Smoothing: A Methodological Analysis’, *Key*

Engineering Materials, 502(February), pp. 19–24.

Robert, A., Roth, S., Chamoret, D., Yan, X.T., Peyraut, F. and Gomes, S. (2012) ‘Functional design method for improving safety and ergonomics of mechanical products’, *Journal of Biomedical Science and Engineering*, 05(08), pp. 457–468.

Rowlands, H. and Bouchereau, V. (1999) ‘Analytical approaches to QFD’, *Manufacturing Engineer*, 78(6), pp. 249–254.

Rumbaugh, J., Jacobson, I. and Booch, G. (2004) *The Unified Modeling Language Reference Manual*.Second. Pearson Education, Inc.

Saaksvuori, A. (2005) *Product Maanagement Lifecycle*.2nd ed. Berlin: Springer.

Sage, A.P. (1996) ‘Manufacturing systems engineering and management’, *1996 IEEE International Conference on Systems, Man and Cybernetics. Information Intelligence and Systems (Cat. No.96CH35929)*. IEEE, Vol.1, pp. 1–9.

Scallan, P. (2003) *Process Planning: The Design/Manufacture Interface*.1st ed. Amsterdam: Butterworth-heinemann.

Schlager, K.J. (1956) ‘Systems Engineering - Key to Modern Development’, *IRE Transactions on Engineering Management*, EM-3(3), pp. 64–66.

Scott, H.A. (1994) ‘Modelling Aircraft Assembly Operations’, *Proceedings of the 1994 Winter Simulation Conference*, , pp. 920–927.

Scott, W. (1993) ‘A330/A340 Cabin Avionics’, *Advanced Avionics on the Airbus A330/A340 and the Boeing-777 Aircraft Conference Proceedings*. London, UK: The Royal Aeronautical Society.

Seabridge, A. (2010a) Integration and Complexity Blockley, R. and Shyy, W. (eds.). *Encyclopedia of Aerospace Engineering*.

Seabridge, A. (2010b) Aircraft Sub-systems Introduction and Overview. *Encyclopedia of Aerospace Engineering*.

Sebaaly, M.F. and Fujimoto, H. (1996) ‘A Genetic Planner for Assembly Automation’, *Proceedings of IEEE International Conference on Evolutionary*

Computation, , pp. 401–406.

Sharma, J.R., Rawani, A.M. and Barahate, M. (2008) ‘Quality function deployment: a comprehensive literature review’, *International Journal of Data Analysis Techniques and Strategies*, 1(1), p. 78.

Shen, W. (2006) ‘IT for Balanced Manufacturing Systems: Collection of papers’, in *IFIP TC5, WG 5.5 Seventh International Conference on Information Technology for Balanced Automation Systems in Manufacturing and Services, Niagra Falls, Ontario, Canada, September 4-6, 2006*. Boston, MA: Springer, pp. 183–192.

Society of Automotive Engineers (2010) *ARP4754A: Guidelines for Development of Civil Aircraft and Systems*. SAE International.

Society of Automotive Engineers (1996) *ARP4761: Guidelines and Methods for Conducting the Safety assessment Process on Civil Airborne Systems and Equipment*. SAE International.

Stark, J. (1992) *Engineering information management systems : beyond CAD/CAM, to concurrent engineering support*. 1st edn. New York: Van Nostrand Reinhold.

Stevens, R. and Brook, P. (1998) *Systems Engineering: Coping with Complexity*.1st ed. Harlow: Prentice Hall Europe.

Systems Engineering Vision Working Group of INCOSE (2007) *Systems Engineering Vision 2020*.2.03.

The Flying Engineer (2013) *Airbus A350 Systems Assembly Model*. Available at: https://theflyingengineer.files.wordpress.com/2013/06/350_22.jpg (Accessed: 10 March 2017).

Thomas, E., Thomas, O., Bianconi, R., Crespo, M. and Daumas, J. (2015) ‘Towards Enhanced Process and Tools for Aircraft Systems Assessments during very Early Design Phase’, *Proceedings of the 11th International Modelica Conference*. Versailles, pp. 831–843.

Tucker, B. (1993) ‘Boeing 777 Primary Flight Control Computer System - Philosophy and Implementation’, *Advanced Avionics on the Airbus A330/A340 and the Boeing-777 Aircraft Conference Proceedings*. London, UK: The Royal Aeronautical Society.

Ulrich, K.T. (2008) *Product design and development*.Fourth. London: McGraw-Hill.

United States Government Accountability Office (2011) *GAO Report: Restructuring Places Program on Firmer Footing , but Progress Still Lagging*. Washington, DC.

United States Government Accountability Office (2012) *GAO Report: DOD Actions Needed to Further Enhance Restructuring and Address Affordability Risks*. Washington, DC.

United States Government Accountability Office (2013) *GAO Report: Current Outlook Is Improved, but Long- Term Affordability is a Major Concern*. Washington, DC.

USA DoD (2015) *Department of Defense Instruction: Operation of the Defense Acquisition System* Department of Defense Chief Information Officer,

USA DoD (1994) *Military Standard MIL-STD 499B Systems Engineering* US Department of Defense,

Vasić, V.S. and Lazarević, M.P. (2008) ‘Standard Industrial Guideline for Mechatronic Product Design’, *FME Transactions*, 36, pp. 103–108.

Verbeek, J. (2013) ‘A Systems Engineering Approach for Development of Aerospace Production Systems’, *SAE Technical Papers*., Vol.7.

Wainwright, W. (1993) ‘A330/A340 Flight Deck’, *Advanced Avionics on the Airbus A330/A340 and the Boeing-777 Aircraft Conference Proceedings*. London, UK: The Royal Aeronautical Society.

Wang, B. (1997) *Integrated Product, Process and Enterprise Design*.1st ed. London: Chapman & Hall.

Weck, O. (2015) *MIT Open Online System & Project Management Course: Design Structure Matrix*. Available at: https://ocw.mit.edu/courses/engineering-systems-division/esd-36-system-project-management-fall-2012/lecture-notes/MITESD_36F12_Lec04.pdf (Accessed: 1 June 2019).

Wei, Y. (2012a) ‘Automatic Generation of Assembly Sequence for the Planning of Outfitting Processes in Shipbuilding’, *Journal of Ship Production and Design*, 28(2), pp. 49–59.

Wei, Y. (2012b) *Automatic Generation of Assembly Sequence for the Planning of Outfitting Processes in Shipbuilding*. Delft University of Technology.

Whitney, D.E. (2004) *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*.1st ed. New York: Oxford University Press.

William, Z. (2006) ‘Benefits of IVHM: An Analytical Approach’, *2006 IEEE Aerospace Conference*. IEEE, pp. 1–9.

Wynn, D., Wyatt, D., Nair, S. and Clarkson, P. (2010) ‘An Introduction to the Cambridge Advanced Modeller’, *Proceedings of the 1st International Conference on Modelling and Management of Engineering Processes (MMEP 2010)*, (November 2015), pp. 19–20.

Wynn, D.C., Nair, S.M.T. and Clarkson, P.J. (2009) ‘The P3 platform: An approach and software system for developing diagrammatic model-based methods in design research’, *DS 58-1: Proceedings of ICED 09, the 17th International Conference on Engineering Design*, 1(August), pp. 559–570.

Xiao, H., Duan, Y. and Zhang, Z. (2018) ‘Mobile 3D assembly process information construction and transfer to the assembly station of complex products’, *International Journal of Computer Integrated Manufacturing*, 31(1) Taylor & Francis, pp. 11–26.

Yeo, C.J. (1981) Fly-by-wire Jaguar, *FLIGHT International*,, p. 816.

Younus, M., Jian, T. and Yuqing, F. (2010) ‘Module-Based Parts Management System Using Single Source of Product Data’, *2010 Second International*

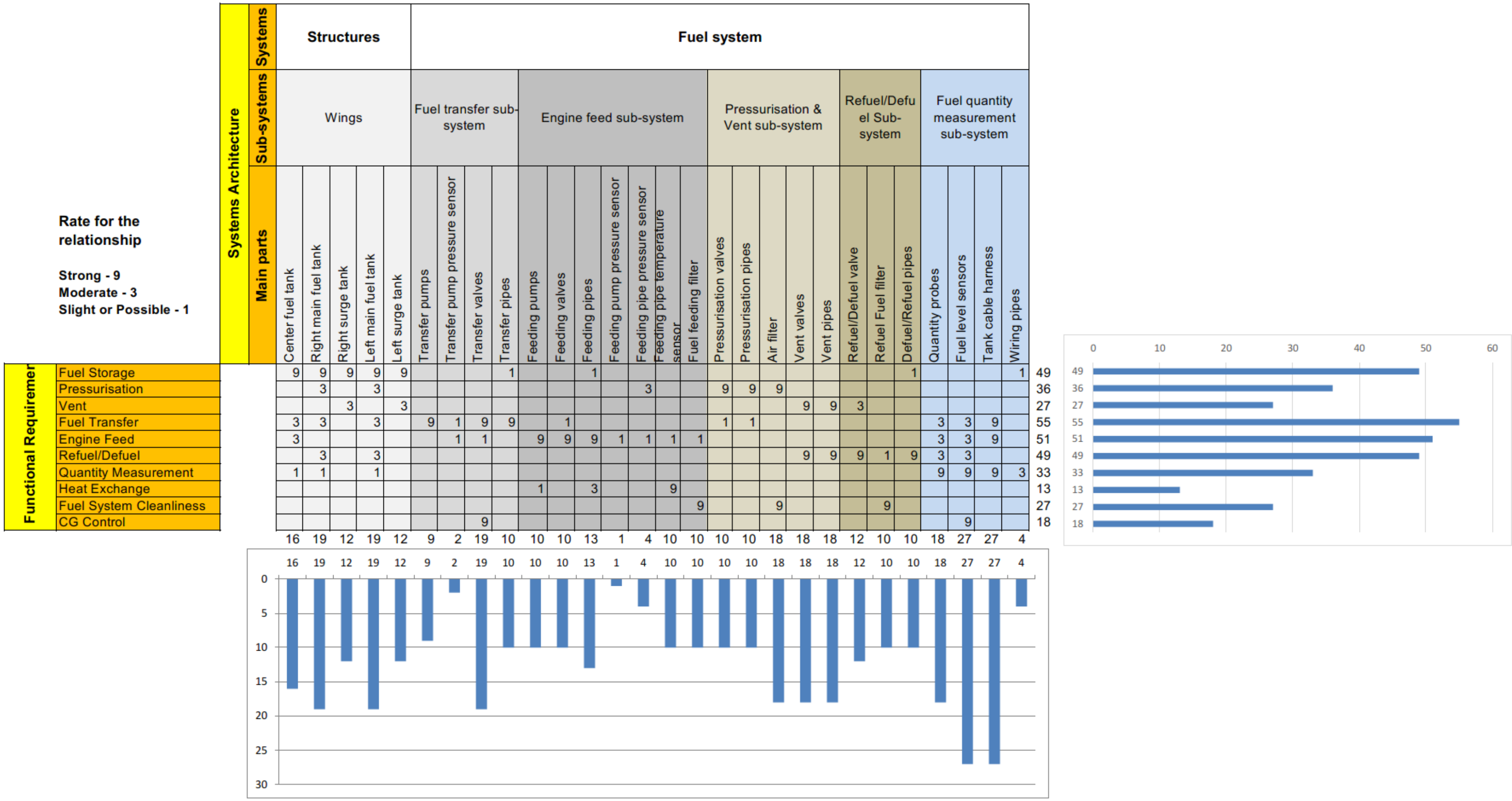
Conference on Computer Research and Development, , pp. 151–155.

Ziarnetzky, T., Mönch, L. and Biele, A. (2014) ‘Simulation of Low-volume Mixed Model Assembly Lines: Modeling Aspects and Case Study’, *Proceedings of the 2014 Winter Simulation Conference*.

APPENDICES

Appendix A Detailed QFD Test Results

This section includes the detailed four-phase QFD approach test results using generic wing section fuel system design information.



Rate for the relationship

Strong - 9
Moderate - 3
Slight or Possible - 1

Systems Architecture	Systems	Structures					Fuel system																							
	Sub-systems	Wings					Fuel transfer sub-system				Engine feed sub-system							Pressurisation & Vent sub-system					Refuel/Defuel Sub-system			Fuel quantity measurement sub-system				
	Main parts	Center fuel tank	Right main fuel tank	Right surge tank	Left main fuel tank	Left surge tank	Transfer pumps	Transfer pump pressure sensor	Transfer valves	Transfer pipes	Feeding pumps	Feeding valves	Feeding pipes	Feeding pump pressure sensor	Feeding pipe pressure sensor	Feeding pipe temperature sensor	Fuel feeding filter	Pressurisation valves	Pressurisation pipes	Air filter	Vent valves	Vent pipes	Refuel/Defuel valve	Refuel Fuel filter	Defuel/Refuel pipes	Quantity probes	Fuel level sensors	Tank cable harness	Wiring pipes	
Functional Requiremer	Fuel Storage	9	9	9	9	9				1			1												1				1	49
	Pressurisation		3		3										3			9	9	9										36
	Vent			3		3															9	9	3							27
	Fuel Transfer	3	3		3		9	1	9	9		1						1	1							3	3	9		55
	Engine Feed	3						1	1		9	9	9	1	1	1	1									3	3	9		51
	Refuel/Defuel		3		3																9	9	9	1	9	3	3			49
	Quantity Measurement	1	1		1																					9	9	9	3	33
	Heat Exchange										1		3			9														13
	Fuel System Cleanliness																9			9				9						27
	CG Control								9																		9			18
		16	19	12	19	12	9	2	19	10	10	10	13	1	4	10	10	10	10	18	18	18	12	10	10	18	27	27	4	

Figure A-1 Deploying functional requirements to systems architecture (phase 2a)

Rate for the relationship

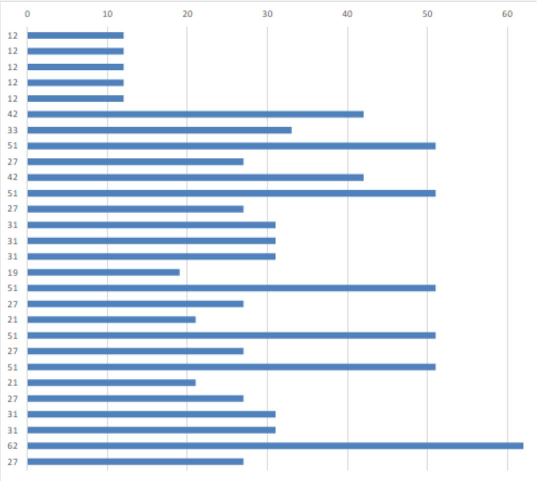
Strong - 9
Moderate - 3
Slight or Possible - 1

Assuming all tanks have these parts

Assuming all valves are electrical controlled

With / Without engine runni

			Test Allocatio	Airtightness test									Wiring connectio				Power-on test	Functional test		Operational test	
			Scenario 4: Test WBS	Fuel transfer sub-system in tank airtightness test	Engine feed sub-system in tank airtightness test	Pressurisation & Vent sub-system in tank airtightness test	Refuel/Defuel sub-system in tank airtightness test	Measurement sub-system in tank airtightness test	Center wing tank and overall sub-systems airtightness test	Right wing tank and overall sub-systems airtightness test	Left wing tank and overall sub-systems airtightness test	Overall system airtightness test after mate and enginee ins.	Center tank wiring connection test	Right wing tank wiring connection test	Left wing tank wiring connection test	Fuel system lower Unit interface connection test	Included in VMS lower interface HIL test	Included in VMS upper interface test	Included in VMS HIL test (fuel system)	Included VMS overall system test (fuel system)	
Systems Architecture	**Systems**	**Sub-systems**	**Main parts**																		
	Structures	Wings	Center fuel tank						9			3									12
			Right main fuel tank							9		3									12
			Right surge tank							9		3									12
			Left main fuel tank								9	3									12
			Left surge tank								9	3									12
	Fuel system	Fuel transfer sub-system	Transfer pumps						3	3	3	3					9	9		9	3	42
			Transfer pump pressure sensor						3	3	3	3					9			9	3	33
			Transfer valves	9					3	3	3	3					9	9		9	3	51
			Transfer pipes	9					3	3	3	9										27
		Engine feed sub-system	Feeding pumps						3	3	3	3					9	9		9	3	42
			Feeding valves		9				3	3	3	3					9	9		9	3	51
			Feeding pipes		9				3	3	3	9										27
			Feeding pump pressure sensor						3	3	3	1					9			9	3	31
			Feeding pipe pressure sensor						3	3	3	1					9			9	3	31
			Feeding pipe temperature sensor						3	3	3	1					9			9	3	31
			Fuel feeding filter		9				3	3	3	1										19
		Pressurisation & Vent sub-system	Pressurisation valves			9			3	3	3	3					9	9		9	3	51
			Pressurisation pipes			9			3	3	3	9										27
			Air filter			9			3	3	3	3										21
			Vent valves			9			3	3	3	3					9	9		9	3	51
			Vent pipes			9			3	3	3	9										27
		Refuel/Defuel Sub-system	Refuel/Defuel valve				9		3	3	3	3					9	9		9	3	51
			Refuel Fuel filter				9		3	3	3	3										21
			Defuel/Refuel pipes				9		3	3	3	9										27
		Fuel quantity measurement sub-system	Quantity probes						3	3	3	1					9			9	3	31
			Fuel level sensors						3	3	3	1					9			9	3	31
			Tank cable harness						3	3	3	1	9	9	9	9	9	1	3	3		62
			Wiring pipes					9	3	3	3	9										27
				18	27	45	27	9	78	87	87	106	9	9	9	126	72	1	120	42	



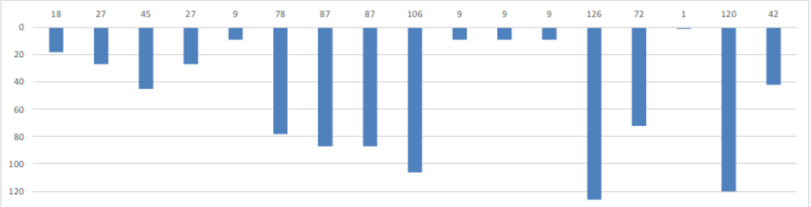
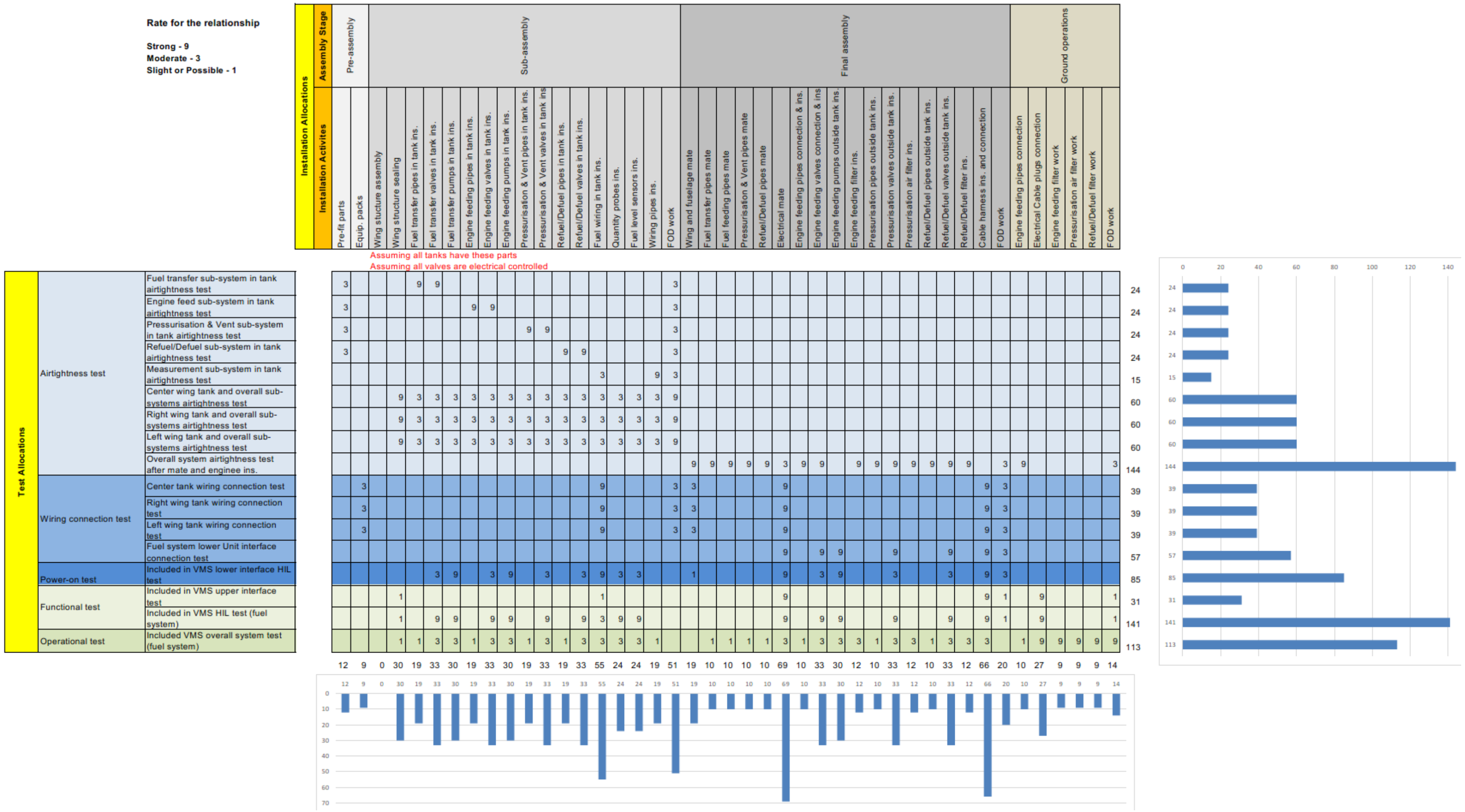


Figure A-2 Deploying systems architecture to tests (phase 3a)



Rate for the relationship

Strong - 9
Moderate - 3
Slight or Possible - 1

Assuming all tanks have these parts
Assuming all valves are electrical controlled

Installation Allocations		Assembly Stage	Pre-assembly		Sub-assembly																	Final assembly																		Ground operations						
		Installation Activites	Pre-fit parts	Equip. packs	Wing stucture assembly	Wing structure sealing	Fuel transfer pipes in tank ins.	Fuel transfer valves in tank ins.	Fuel transfer pumps in tank ins.	Engine feeding pipes in tank ins.	Engine feeding valves in tank ins.	Engine feeding pumps in tank ins.	Pressurisation & Vent pipes in tank ins.	Pressurisation & Vent valves in tank ins	Refuel/Defuel pipes in tank ins.	Refuel/Defuel valves in tank ins.	Fuel wiring in tank ins.	Quantity probes ins.	Fuel level sensors ins.	Wiring pipes ins.	FOD work	Wing and fuselage mate	Fuel transfer pipes mate	Fuel feeding pipes mate	Pressurisation & Vent pipes mate	Refuel/Defuel pipes mate	Electrical mate	Engine feeding pipes connection & ins.	Engine feeding valves connection & ins	Engine feeding pumps outside tank ins.	Engine feeding filter ins.	Pressurisation pipes outside tank ins.	Pressurisation valves outside tank ins.	Pressurisation air filter ins.	Refuel/Defuel pipes outside tank ins.	Refuel/Defuel valves outside tank ins.	Refuel/Defuel filter ins.	Cable harness ins. and connection	FOD work	Engine feeding pipes connection	Electrical Cable plugs connection	Engine feeding filter work	Pressurisation air filter work	Refuel/Defuel filter work	FOD work	
Test Allocations	Airtightness test	Fuel transfer sub-system in tank airtightness test	3				9	9													3																									24
		Engine feed sub-system in tank airtightness test	3							9	9										3																									24
		Pressurisation & Vent sub-system in tank airtightness test	3										9	9							3																									24
		Refuel/Defuel sub-system in tank airtightness test	3												9	9					3																									24
		Measurement sub-system in tank airtightness test															3			9	3																									15
		Center wing tank and overall sub-systems airtightness test				9	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9																									60
		Right wing tank and overall sub-systems airtightness test				9	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9																									60
		Left wing tank and overall sub-systems airtightness test				9	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9																									60
		Overall system airtightness test after mate and enginee ins.																				9	9	9	9	9	3	9	9		9	9	9	9	9	9	9		3	9					3	144
	Wiring connection test	Center tank wiring connection test		3													9				3	3					9											9	3							39
		Right wing tank wiring connection test		3													9				3	3					9											9	3							39
		Left wing tank wiring connection test		3													9				3	3					9											9	3							39
		Fuel system lower Unit interface connection test																									9		9	9			9			9		9	3							57
	Power-on test	Included in VMS lower interface HIL test						3	9		3	9		3		3	9	3	3			1					9		3	9			3			3		9	3							85
	Functional test	Included in VMS upper interface test				1											1										9											9	1		9				1	31
		Included in VMS HIL test (fuel system)				1		9	9		9	9		9		9	3	9	9								9		9	9			9			9		9	1		9				1	141
	Operational test	Included VMS overall system test (fuel system)				1	1	3	3	1	3	3	1	3	1	3	3	3	3	1			1	1	1	1	3	1	3	3	3	1	3	3	1	3	3	3		1	9	9	9	9	9	113
			12	9	0	30	19	33	30	19	33	30	19	33	19	33	55	24	24	19	51	19	10	10	10	10	69	10	33	30	12	10	33	12	10	33	12	66	20	10	27	9	9	9	14	

Figure A-3 Deploying tests to installations (phase 3b)

Rate for the relationship

Strong - 9
Moderate - 3
Slight or Possible - 1

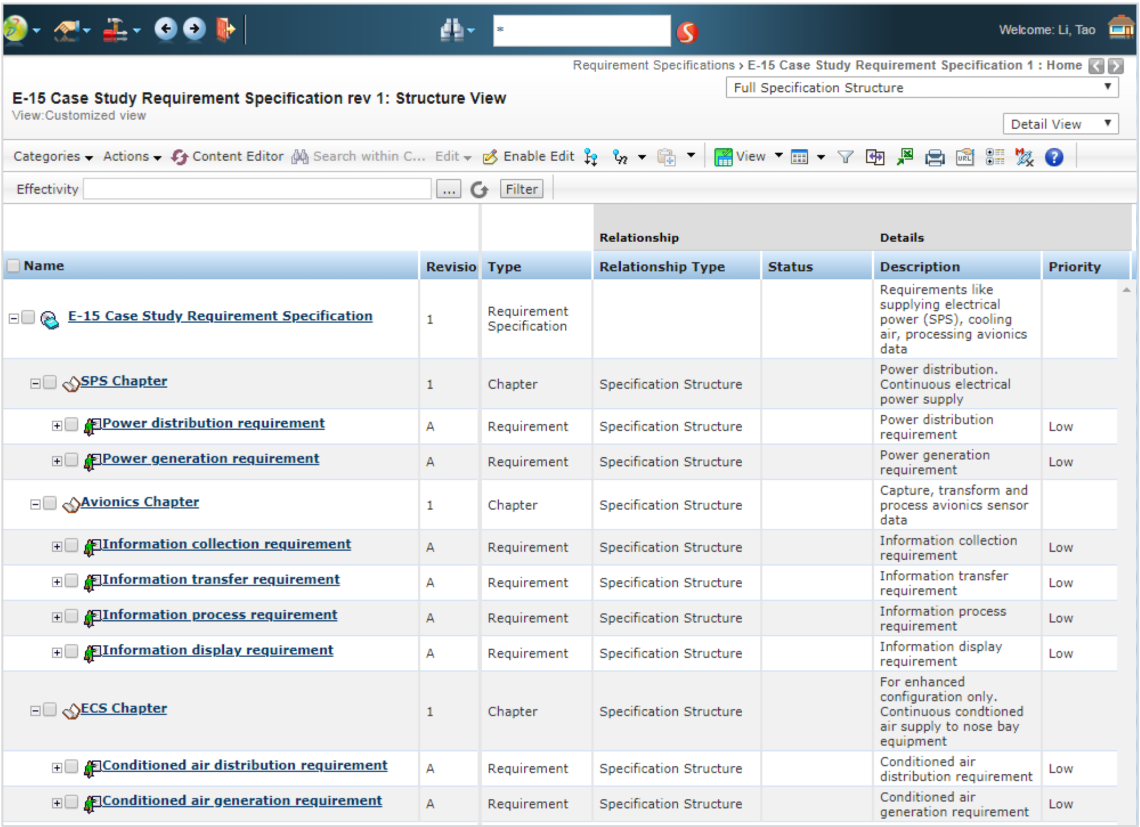
	Assembly Stage	Installation Activites	Operations / Facilites	Warehouse / Feeder line assemlby	Pre-test facility	Pre-fit and pre-assembly rig	Structure assembly platform	sub-assembly platform	Mate assembly stand	Final assembly stand	Aircraft wiring test	Functional test rig stand	Final check out stand	Ground operational test hanger	Crew station stand
Installation Allocations	Pre-assembly	Pre-fit parts		3	9	9									
		Equip. packs		9	9										
	Sub-assembly	Wing stucture assembly					9								
		Wing structure sealing					9								
		Fuel transfer pipes in tank ins.					3	9							
		Fuel transfer valves in tank ins.					3	9							
		Fuel transfer pumps in tank ins.					3	9							
		Engine feeding pipes in tank ins.					3	9							
		Engine feeding valves in tank ins.					3	9							
		Engine feeding pumps in tank ins.					3	9							
		Pressurisation & Vent pipes in tank ins.					3	9							
		Pressurisation & Vent valves in tank ins.					3	9							
		Refuel/Defuel pipes in tank ins.					3	9							
		Refuel/Defuel valves in tank ins.					3	9							
		Fuel wiring in tank ins.						9							
		Quantity probes ins.						9							
		Fuel level sensors ins.						9							
		Wiring pipes ins.					1	9							
		FOD work		1	1	1	9	9							
	Final assembly	Wing and fuselage mate							9						
		Fuel transfer pipes pipes mate							9						
		Fuel feeding pipes pipes mate							9						
		Pressurisation & Vent pipes mate							9						
		Refuel/Defuel pipes mate							9						
		Electrical mate							9						
		Engine feeding pipes connection & ins.								9					
		Engine feeding valves connection & ins.								9					
		Engine feeding pumps outside tank ins.								9					
		Engine feeding filter ins.								9					
		Pressurisation pipes outside tank ins.							1	9					
		Pressurisation valves outside tank ins.							1	9					
		Pressurisation air filter ins.							1	9					
		Refuel/Defuel pipes outside tank ins.							1	9					
		Refuel/Defuel valves outside tank ins.							1	9					
		Refuel/Defuel filter ins.							1	9					
		Cable harness ins. and connection							1	9	9	3	1		
		FOD work							3	3	3	1	3		
	Ground operations	Engine feeding pipes connection												3	9
		Electrical Cable plugs connection												9	9
		Engine feeding filter work												3	9
		Pressurisation air filter work												3	9
		Refuel/Defuel filter work												3	9
		FOD work												3	3

Figure A-4 Deploying installations to operations/facilities (phase 3c)

Appendix B E-15 Case Study Results

B.1 E-15 modelling results

B.1.1 E-15 requirement model



Requirement Specifications › E-15 Case Study Requirement Specification 1 : Home

E-15 Case Study Requirement Specification rev 1: Structure View
View:Customized view

			Relationship		Details	
Name	Revisio	Type	Relationship Type	Status	Description	Priority
E-15 Case Study Requirement Specification	1	Requirement Specification			Requirements like supplying electrical power (SPS), cooling air, processing avionics data	
SPS Chapter	1	Chapter	Specification Structure		Power distribution. Continuous electrical power supply	
Power distribution requirement	A	Requirement	Specification Structure		Power distribution requirement	Low
Power generation requirement	A	Requirement	Specification Structure		Power generation requirement	Low
Avionics Chapter	1	Chapter	Specification Structure		Capture, transform and process avionics sensor data	
Information collection requirement	A	Requirement	Specification Structure		Information collection requirement	Low
Information transfer requirement	A	Requirement	Specification Structure		Information transfer requirement	Low
Information process requirement	A	Requirement	Specification Structure		Information process requirement	Low
Information display requirement	A	Requirement	Specification Structure		Information display requirement	Low
ECS Chapter	1	Chapter	Specification Structure		For enhanced configuration only. Continuous condtioned air supply to nose bay equipment	
Conditioned air distribution requirement	A	Requirement	Specification Structure		Conditioned air distribution requirement	Low
Conditioned air generation requirement	A	Requirement	Specification Structure		Conditioned air generation requirement	Low

Figure B-1 Structure top view of E-15 Requirement in ENOVIA PLM system

The requirement specification hierarchy exported from ENOVIA PLM system is shown in table B-1.

Table B-1 E-15 requirement specification hierarchy

Level	Name	Revision	Type	Relationship Type	Classification
1	E-15 Case Study Requirement Specification	1	Requirement Specification		
2	SPS Chapter	1	Chapter	Specification Structure	
3	Power distribution requirement	A	Requirement	Requirement	Functional
4	Nose bay power distribution sub-requirement	A	Requirement	Sub Requirement	Functional

Table B-1 (continued)

4	Cockpit power distribution sub-requirement	A	Requirement	Sub Requirement	Functional
4	Other section power distribution sub-requirement	A	Requirement	Sub Requirement	Functional
3	Power generation requirement	A	Requirement	Specification Structure	Functional
4	Other section power generation sub-requirement	A	Requirement	Sub Requirement	Functional
2	Avionics Chapter	1	Chapter	Specification Structure	
3	Information collection requirement	A	Requirement	Requirement	Functional
4	Nose bay information collection sub-requirement	A	Requirement	Sub Requirement	Functional
4	Other section information collection sub-requirement	A	Requirement	Sub Requirement	Functional
3	Information transfer requirement	A	Requirement	Specification Structure	Functional
4	Nose bay information transfer sub-requirement	A	Requirement	Sub Requirement	Functional
4	Cockpit information transfer sub-requirement	A	Requirement	Sub Requirement	Functional
4	Other section information transfer sub-requirement	A	Requirement	Sub Requirement	Functional
3	Information process requirement	A	Requirement	Specification Structure	
4	Nose bay information process sub-requirement	A	Requirement	Sub Requirement	Functional
4	Cockpit information process sub-requirement	A	Requirement	Sub Requirement	Functional
3	Information display requirement	A	Requirement	Specification Structure	
4	Cockpit information display sub-requirement	A	Requirement	Sub Requirement	Functional
2	ECS Chapter	1	Chapter	Specification Structure	
3	Conditioned air distribution requirement	A	Requirement	Specification Structure	
4	Nose bay conditioned air distribution sub-requirement	A	Requirement	Sub Requirement	Functional
4	Cockpit conditioned air distribution sub-requirement	A	Requirement	Sub Requirement	Functional
4	Other section conditioned air distribution sub-requirement	A	Requirement	Sub Requirement	Functional
3	Conditioned air generation requirement	A	Requirement	Specification Structure	
4	Other section conditioned air generation sub-requirement	A	Requirement	Sub Requirement	Functional

B.1.2 E-15 functional and logical model

Although efforts have been made to reduce the modelling items in the E-15 case study, there are still too many information provided in the CATIA V6 software viewpoint. The functional and logical models are represented in simplified 2D block diagrams to have a clear view. This includes models at each level and interactions between them.

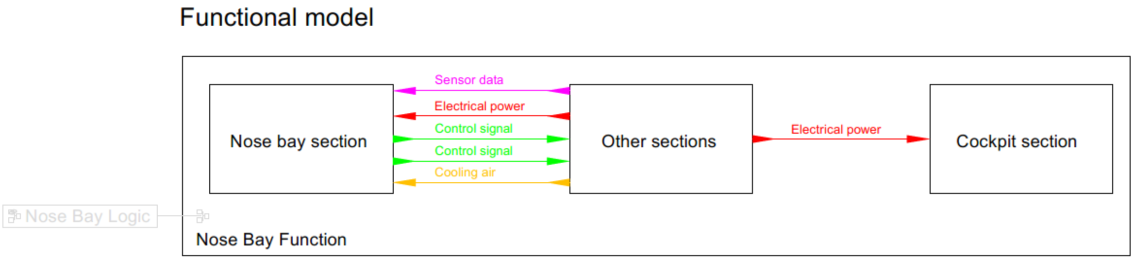


Figure B-2 E-15 top-level functional model

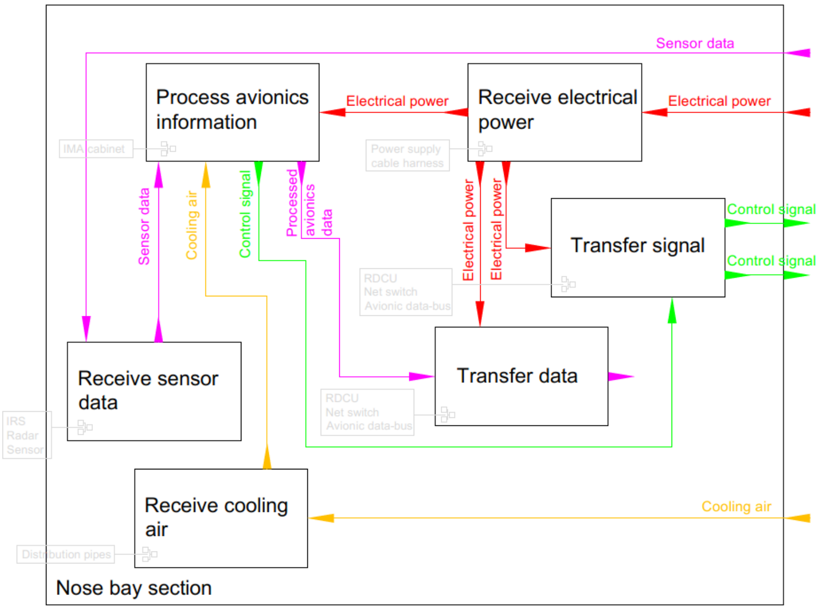


Figure B-3 E-15 nose bay section functional model

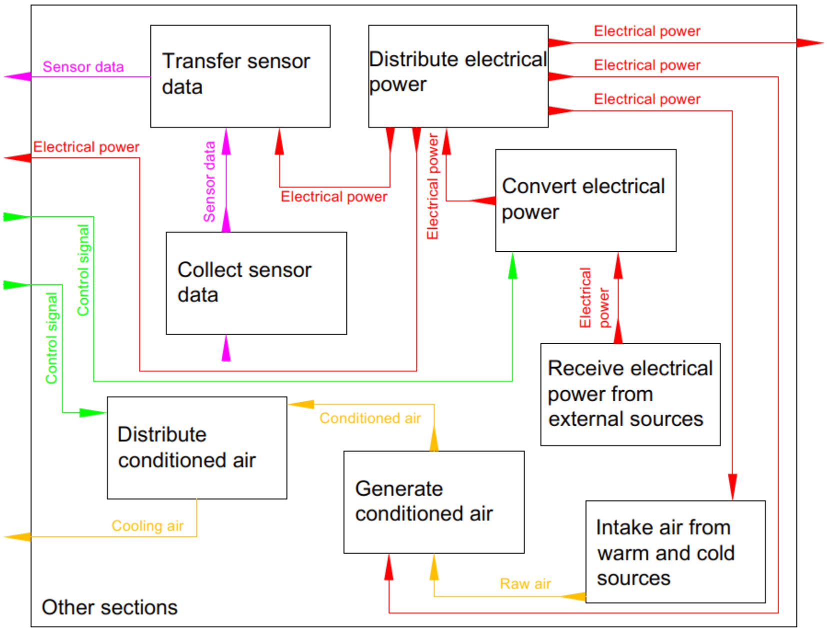


Figure B-4 E-15 other section functional model

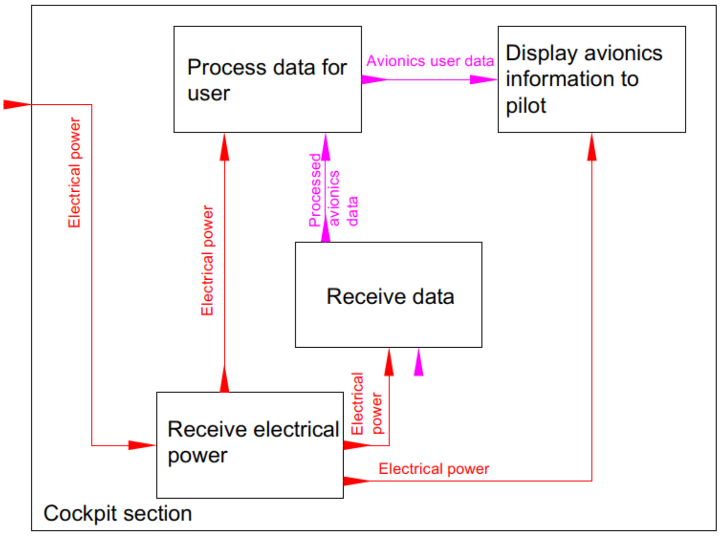


Figure B-5 E-15 cockpit section functional model

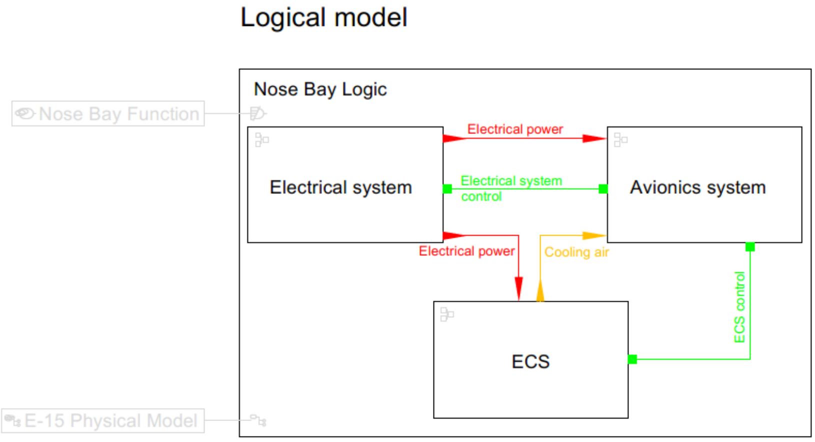


Figure B-6 E-15 top-level logical model

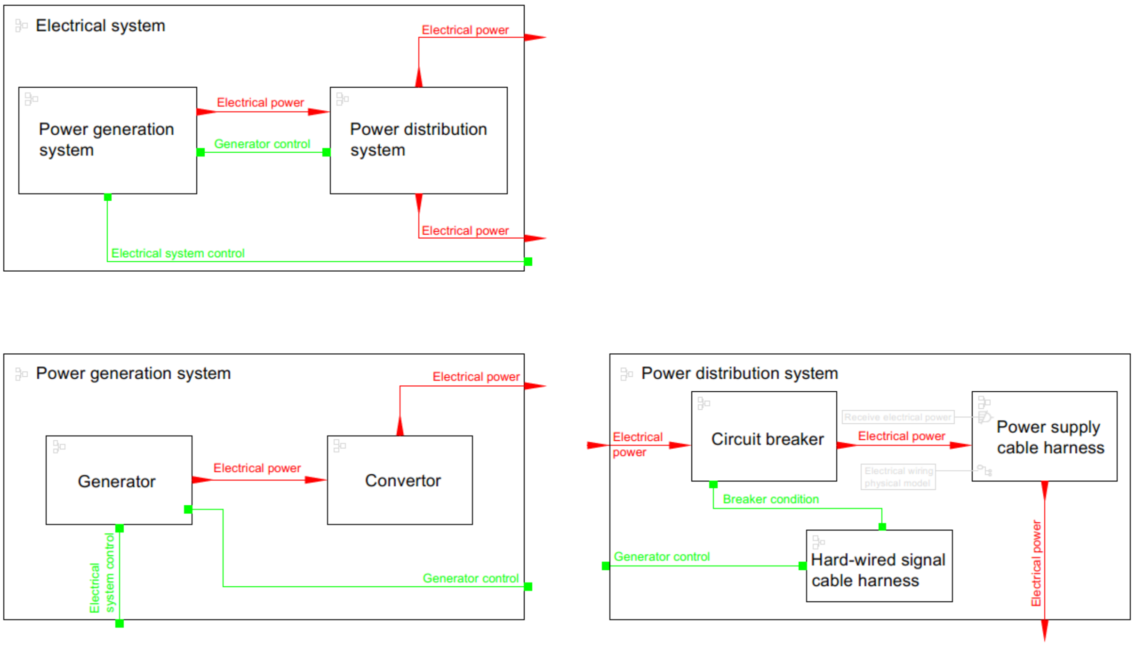


Figure B-7 E-15 electrical system and sub-system logical models

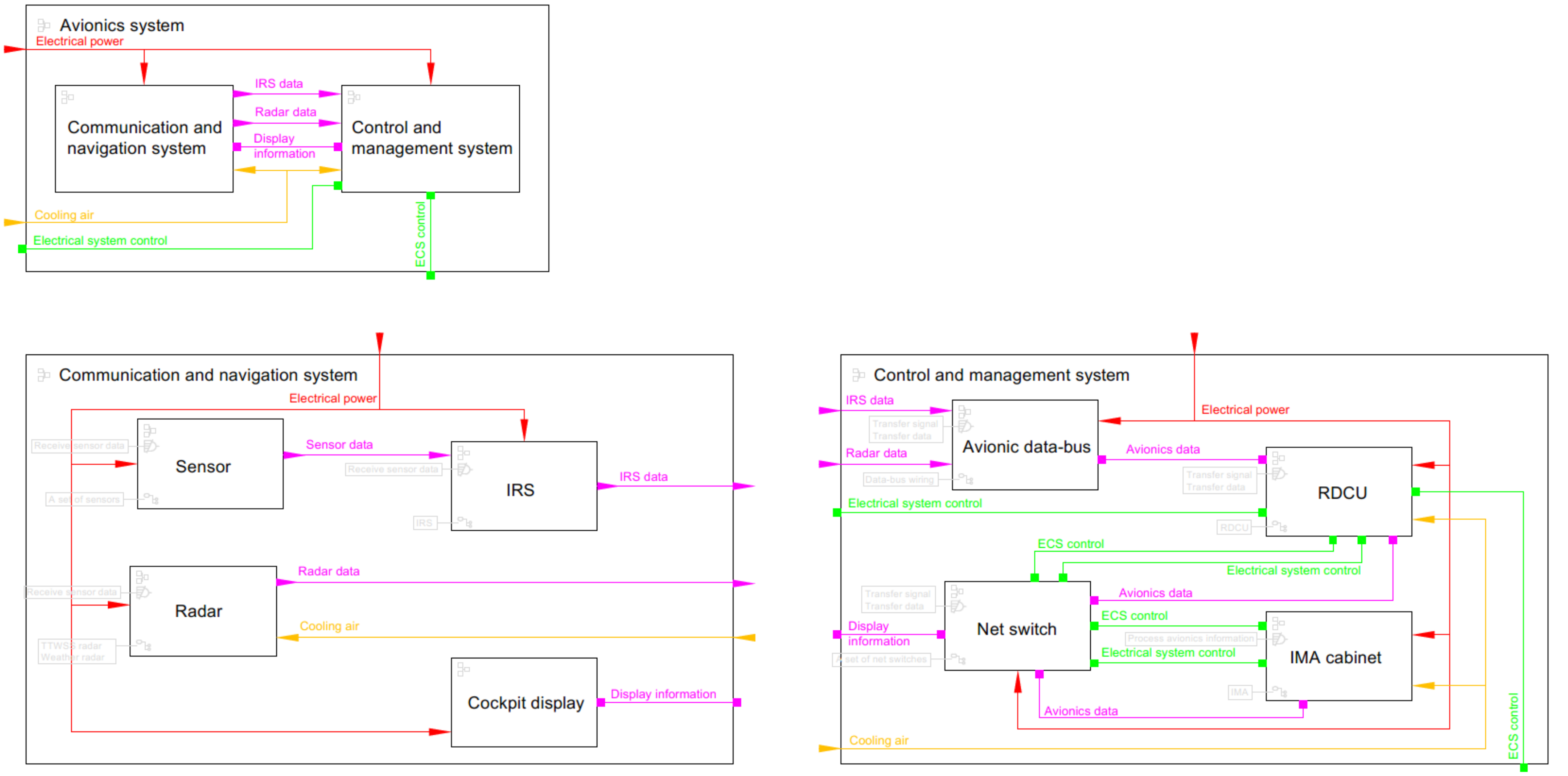


Figure B-8 E-15 avionics system and sub-system logical models

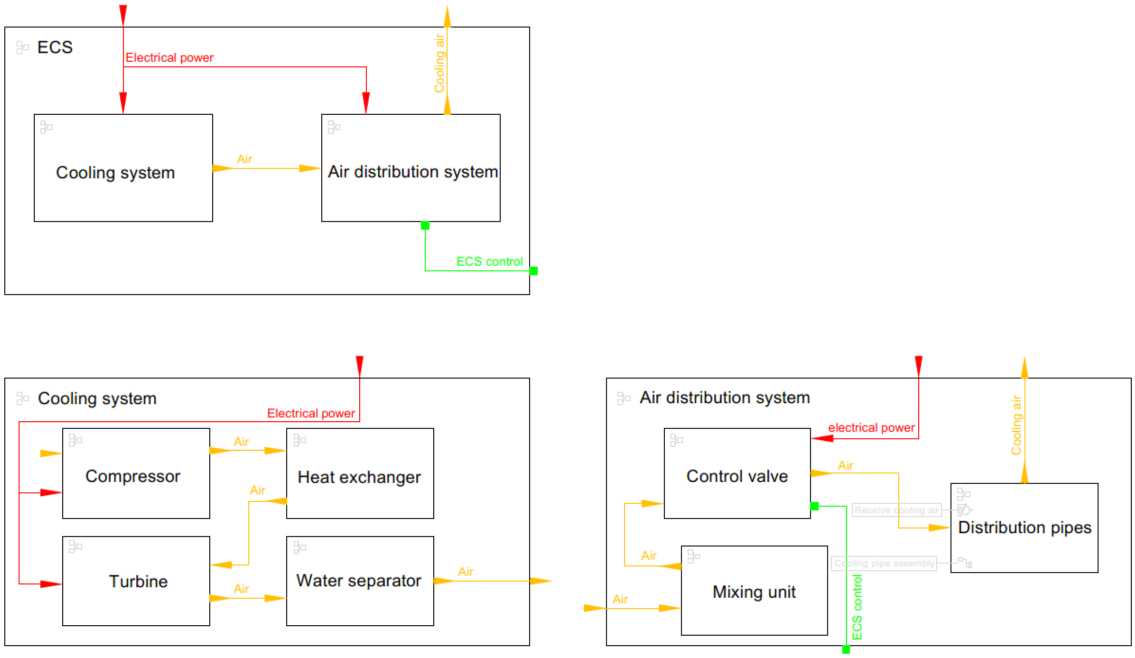
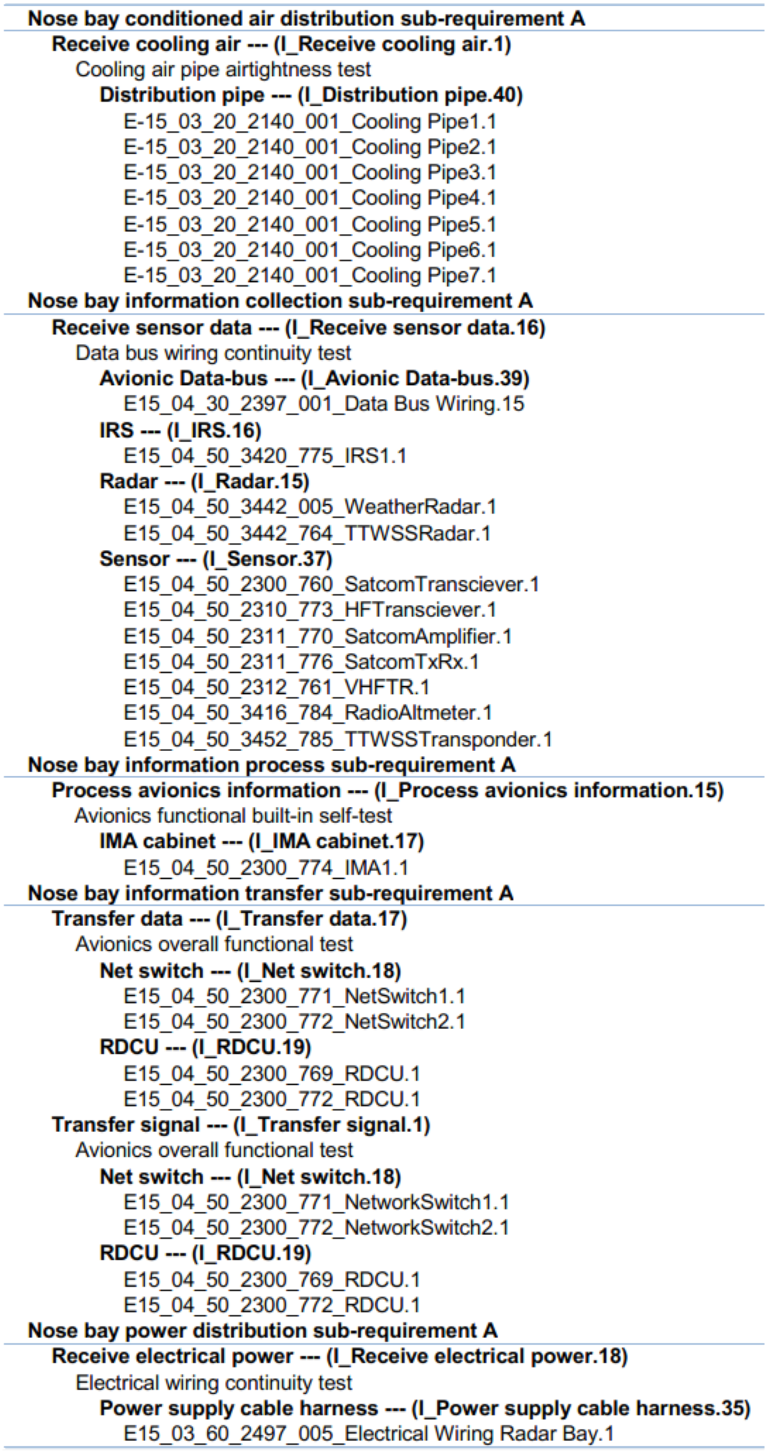


Figure B-9 E-15 ECS and its sub-system logical models

B.2 E-15 requirement traceability results

The extracted RFLP traceability links are shown in figure B-10. The associated functional tests are also combined in it. This result is presented as the following manner: “Requirement – Functional model – Integration test – Logical model – Physical item”.



- **Nose bay conditioned air distribution sub-requirement A**
  - **Receive cooling air --- (I_Receive cooling air.1)**
    - Cooling air pipe airtightness test
      - **Distribution pipe --- (I_Distribution pipe.40)**
        - E-15_03_20_2140_001_Cooling Pipe1.1
        - E-15_03_20_2140_001_Cooling Pipe2.1
        - E-15_03_20_2140_001_Cooling Pipe3.1
        - E-15_03_20_2140_001_Cooling Pipe4.1
        - E-15_03_20_2140_001_Cooling Pipe5.1
        - E-15_03_20_2140_001_Cooling Pipe6.1
        - E-15_03_20_2140_001_Cooling Pipe7.1
- **Nose bay information collection sub-requirement A**
  - **Receive sensor data --- (I_Receive sensor data.16)**
    - Data bus wiring continuity test
      - **Avionic Data-bus --- (I_Avionic Data-bus.39)**
        - E15_04_30_2397_001_Data Bus Wiring.15
      - **IRS --- (I_IRS.16)**
        - E15_04_50_3420_775_IRS1.1
      - **Radar --- (I_Radar.15)**
        - E15_04_50_3442_005_WeatherRadar.1
        - E15_04_50_3442_764_TTWSSRadar.1
      - **Sensor --- (I_Sensor.37)**
        - E15_04_50_2300_760_SatcomTransciever.1
        - E15_04_50_2310_773_HFTransciever.1
        - E15_04_50_2311_770_SatcomAmplifier.1
        - E15_04_50_2311_776_SatcomTxRx.1
        - E15_04_50_2312_761_VHFTR.1
        - E15_04_50_3416_784_RadioAltmeter.1
        - E15_04_50_3452_785_TTWSSTransponder.1
- **Nose bay information process sub-requirement A**
  - **Process avionics information --- (I_Process avionics information.15)**
    - Avionics functional built-in self-test
      - **IMA cabinet --- (I_IMA cabinet.17)**
        - E15_04_50_2300_774_IMA1.1
- **Nose bay information transfer sub-requirement A**
  - **Transfer data --- (I_Transfer data.17)**
    - Avionics overall functional test
      - **Net switch --- (I_Net switch.18)**
        - E15_04_50_2300_771_NetSwitch1.1
        - E15_04_50_2300_772_NetSwitch2.1
      - **RDCU --- (I_RDCU.19)**
        - E15_04_50_2300_769_RDCU.1
        - E15_04_50_2300_772_RDCU.1
  - **Transfer signal --- (I_Transfer signal.1)**
    - Avionics overall functional test
      - **Net switch --- (I_Net switch.18)**
        - E15_04_50_2300_771_NetworkSwitch1.1
        - E15_04_50_2300_772_NetworkSwitch2.1
      - **RDCU --- (I_RDCU.19)**
        - E15_04_50_2300_769_RDCU.1
        - E15_04_50_2300_772_RDCU.1
- **Nose bay power distribution sub-requirement A**
  - **Receive electrical power --- (I_Receive electrical power.18)**
    - Electrical wiring continuity test
      - **Power supply cable harness --- (I_Power supply cable harness.35)**
        - E15_03_60_2497_005_Electrical Wiring Radar Bay.1

Figure B-10 E-15 extracted traceability links with integration tests

Appendix C B777 Case Study Results

C.1 B777 requirements document

C.1.1 B777 requirements creating rule

The B777 requirements document is created to meet ENOVIA V6 requirement management needs. The requirements document follow the structure arrangement and numbering rule as shown in table C-1.

Table C-1 Instructions for B777 requirements document

Product hierarchy	ENOVIA V6 modelling rule	Content	Document numbering example	Note
N/A	Requirement specification	Top level of specification structure, enables to decompose the captured requirements into smaller constituents	Document title	Database management
N/A	Chapter	Document element in a specification structure, used for store, classify, and easily retrieve the requirements	Sorted by major system names	Database management

Table C1 (continued)

Aircraft	N/A	Brief description of aircraft general	1. Aircraft general	Chapter name
	Requirement	Functional and non-functional requirements at aircraft level	1.1 Payload accommodation 1.2 Target performance 1.3 Flight envelope	
	Sub-requirement	Decomposed aircraft level requirements	1.2.1 Mission performance 1.2.2 Climb performance	
System	Requirement	Brief description of system general	2. Fuel system 3. ECS	Chapter name
Sub-system	Requirement (first level)	Functional and non-functional requirement at sub-system level	2.1 Engine feed sub-system	
	Sub-requirement (second level)	Decomposed sub-system level requirements	2.1.1 Feed pumping 2.1.2 Cross-feed	
Component	Sub-requirement (bottom level)	Decomposed component level requirement	2.1.2.1 Feed shut-off valve	If required

C.1.2 B777 requirement model

Note: this requirement model template can be used for generic systems design, but in this case study it only considers the case study needs and assembly relevant requirements. A requirement template is shown later in this section. All requirements in the B777 case study are captured from published resources including:

- EASA, Certification Specifications for Large Aeroplanes CS-25, 2007
- Moir and Seabridge, Aircraft systems: Mechanical, electrical, and avionics subsystems integration, 2008
- Moir and Seabridge, Design and Development of Aircraft Systems, 2013
- Langton, Clark, Hewitt and Richards, Aircraft Fuel System, 2009
- Lufthansa Technical Training GmbH, Boeing 777 Training Manual - ATA Quick Reference General, 2013
- SMARTCOCKPIT.COM, Boeing B777 – Systems Summary Electrical, online
- SMARTCOCKPIT.COM, Boeing B777 – Systems Summary Fuel, online

This requirements model is captured in a template created by the author. Some sub-sections are left in blank due to they are not relevant in this case study.

1. Aircraft general chapter

- ➢ General aircraft level technical specifications
- ➢ In this case study, the fuel system, ECS, electrical system in the wing section shall work together to achieve system-wide information management.
- ➢ System design shall support later manufacturing and operations in service.

1.1. Payload accommodation

1.2. Target performance

1.2.1. Mission performance

1.2.2. Climb performance

1.2.3. Field performance

1.2.4. Payload and range characteristics

1.3. Flight envelope

1.3.1. Operational speed limitations

1.3.2. Maximum flight level

1.4. Weight

1.4.1. Design weight

1.4.2. Fuel weight

1.4.3. Empty weight and corresponding centre of gravity

CS 25.29: (a) The empty weight and corresponding centre of gravity must be determined by weighing the aeroplane with – (1) Fixed ballast; (2) Unusable fuel determined under CS 25.959; and (3) Full operating fluids, including – (i) Oil; (ii) Hydraulic fluid; and (iii) Other fluids required for normal operation of aeroplane systems, except potable water, lavatory pre-charge water, and fluids intended for injection in the engine. (b) The condition of the aeroplane at the time of determining empty weight must be one that is well defined and can be easily repeated.

1.4.4. Centre of gravity limits

CS 25.27: The extreme forward and the extreme aft centre of gravity limitations must be established for each practicably separable operating condition. No such limit may lie beyond – (a) The extremes selected by the applicant; (b) the extremes within which the structure is proven; or (c) The extremes within which compliance with each applicable flight requirement is shown.

1.5. Airport compatibility

1.6. Fatigue life

1.7. Economy

The economy shall include aircraft operational cost.

1.7.1. Fuel efficiency

For example: Boeing 777 200LR: 8,297 L/hr fuel burn when cruising at 892km/h, Boeing 777-300ER: 9,206 L/hr fuel burn when cruising at 892km/h

1.8. Environment

1.8.1. Emissions

Aircraft shall reduce carbon dioxide (CO2) and nitrogen oxide (NOx) emissions

1.8.2. Noise

NASA report: aircraft shall control noise level. The ground noise level shall be measured at 8,000ft, 15,000ft and 30,000ft.

1.9. Loading distribution

CS25.23: Ranges of weights and centres of gravity within which the aeroplane may be safely operated must be established. If a weight and centre of gravity combination is allowable only within certain load distribution limits (such as spanwise) that could be inadvertently exceeded, these limits and the corresponding weight and centre of gravity combinations must be established.

1.9.1. Aerodynamic load distribution

1.9.2. Inertia distribution

2. Fuel system chapter

- Fuel system general technical specifications
- CS 25.961 The weight of the aeroplane must be the weight with full fuel tanks, minimum crew, and the ballast necessary to maintain the centre of gravity within allowable limits.
- Fuel system shall supply fuel to the engines and the APU. The fuel shall be contained in a centre tank, and left and right main tanks.
- Fuel shall be transferred efficiently and safely in pre-defined orders through engine feed, APU feed, refuelling/defueling and jettison sub-systems in all the system operation processes.
- Fuel system shall work cooperate with other systems to achieve high speed fuel system information management.

2.1. Fuel storage

Fuel shall be stored safely in fuel tanks during all the system operation processes.

Fuel storage specifications:

For example (SMARTCOCKPIT.COM): maximum fuel capacity: 181,283 Litres (47,890 US Gal)

2.1.1. Fuel tank location

The fuel tank location shall consider the aircraft gravity balancing in all aircraft operations.

2.1.2. Fuel tank installation

CS 25.967 Fuel tank installations: (b) Spaces adjacent to tank surfaces must be ventilated to avoid fume accumulation due to minor leakage. If the tank is in a sealed compartment, ventilation may be limited to drain holes large enough to prevent excessive pressure resulting from altitude changes.

2.1.3. Fuel tank test

CS 25.965 Fuel tank tests: It must be shown by tests that the fuel tanks, as mounted in the aeroplane can withstand, without failure or leakage.

CS 25.975 Fuel tank vents: (3) The venting capacity and vent pressure levels must maintain acceptable differences of pressure between the interior and exterior of the tank, during – (i) Normal flight operation; (ii) Maximum rate of ascent and descent; and (iii) Refuelling and defueling (where applicable).

2.2. Engine feed sub-system

CS 25.953 Fuel system independence: each fuel system must meet the requirements of CS 25.903(b) by – (a) Allowing the supply of fuel to each engine through a system independent of each part of the system supplying fuel to any other engine; or (b) Any other acceptable method.

System component and pump design shall consider the inlet design such that the ingestion of FOD is minimized.

2.2.1. Feed pumping

The feed system shall use override pumping system to provide the correct fuel burn sequencing. The same pump system shall also provide jettison function. The location of these pumps shall consider installation and maintenance requirements. The pumps shall switch automatically once the fuel in the centre tank is empty (Langton, Clark, Hewitt and Richards, 2009).

In the unlikely loss of both engine feed pumps, the engine shall operate in suction feed mode at altitudes up to about 25,000 ft (SMARTCOCKPIT.COM).

Fuel pumps shall not run dry beyond their qualified level. If fuel pumps can be uncovered during normal operation, pumps shall be shut down automatically and that the shutdown feature is sufficiently robust such that erroneous pump running does not cause a hazard (SMARTCOCKPIT.COM).

2.2.2. Cross-feed

Cross-feed shall be used to provide via two separate isolation valves connected in parallel and located on the left side of the aircraft (Langton, Clark, Hewitt and Richards, 2009). This redundant solution shall ensure continued availability of function following any single failure which may be critical in ETOPS operations (SMARTCOCKPIT.COM).

2.2.3. Over pressure protection

Thermal relief valves shall be used to protect the feed manifold from over pressure by relieving any excess pressure into their respective main wing tanks (Langton, Clark, Hewitt and Richards, 2009).

2.2.4. Manifold and piping

CS 25.993 Fuel system lines and fittings: (b) each fuel line connected to components of the aeroplane between which relative motion could exist must have provisions for flexibility.

The override pump outlets shall be connected to the engine feed manifold via check valves to protect the integrity of the feed line (Langton, Clark, Hewitt and Richards, 2009).

2.3. Fuel vent sub-system

CS 25.975 Fuel tank vents: (a) each fuel tank must be vented from the top part of the expansion space so that venting is effective under any normal flight condition. (4) Airspaces of tanks with interconnected outlets must be interconnected.

2.3.1. Surge tank configuration

Surge tanks shall be provided in each wing, outboard of each main tank.

2.3.2. Tank and system protection

Vent system shall also have a relatively sophisticated pressure relief system to protect the structure from over-pressure situations (Langton, Clark, Hewitt and Richards, 2009).

Each surge tank shall have equipment to recover outside air dynamic pressure and protect the fuel system from the possibility of a direct lightning strike igniting fuel vapours and propagating the resulting combustion into the fuel tanks (Langton, Clark, Hewitt and Richards, 2009).

The surge tank also shall have a re-settable relief valve that opens when a pre-determined pressure differential occurs in either direction between the outside air and the surge tank (Langton, Clark, Hewitt and Richards, 2009).

2.3.3. Fuel drain

At the outboard locations, float actuated vent valves shall close off the vent system when fuel is present thus preventing fuel from entering the surge tank. If any fuel gets into the surge tank, a check valve between the surge tank and the main wing tank shall allow fuel to drain back into the main tank after take-off when the outboard wing tip is high (Langton, Clark, Hewitt and Richards, 2009).

2.3.4. Manifold and piping

CS 25.993 Fuel system lines and fittings: (b) each fuel line connected to components of the aeroplane between which relative motion could exist must have provisions for flexibility.

The tank vent lines are formed using vent channels formed using ‘Hat’ section stringers instead on conventional piping (Langton, Clark, Hewitt and Richards, 2009).

2.4. Pressure refuelling sub-system

CS 25.979 Pressure fuelling systems: (b) An automatic shut-off means must be provided to prevent the quantity of fuel in each tank from exceeding the maximum quantity approved for that tank. This means must – (1) Allow checking for proper shut-off operation before each fuelling of the tank; and (2)

Provide indication, at each fuelling station, of failure of the shut-off means to stop the fuel flow at the maximum quantity approved for that tank. A means must be provided to prevent damage to the fuel system in the event of failure of the automatic shut-off means prescribed in subparagraph (b) of this paragraph. (d) The aeroplane pressure fuelling system (not including fuel tanks and fuel tank vents) must withstand an ultimate load that is 2.0 times the load arising from the maximum pressures, including surge, that is likely to occur during fuelling. The maximum surge pressure must be established with any combination of tank valves being either intentionally or inadvertently closed.

2.4.1. Refuelling system configuration

The pressure refuelling station including the integrated refuel and display panel shall be located at the easy access place of the wing. Manifold drain valves shall also be included in the pressure refuelling system (Langton, Clark, Hewitt and Richards, 2009). The refuel shut-off valves in the fuel tanks shall be controlled by the switches on the integrated refuel panel (SMARTCOCKPIT.COM).

2.4.2. Refuelling control

The integrated refuel and display panel shall provide auto-refuelling by pre-setting the total fuel load required. The refuel valves shall also close when the maximum volume for that tank is reached (Langton, Clark, Hewitt and Richards, 2009). The system test switch on the refuel panel shall provide the pre-check function. When auto-refuelling is in process, pushing the test switch shall cause the refuel valves to close and open automatically as auto-refuelling is resumed (SMARTCOCKPIT.COM).

2.4.3. Weight control

Weight distribution between fuel tanks shall be managed automatically and the appropriate refuel valves are selected closed when the correct weight in each tank is met (Langton, Clark, Hewitt and Richards, 2009).

2.4.4. Manifold and piping

CS 25.993 Fuel system lines and fittings: (b) each fuel line connected to components of the aeroplane between which relative motion could exist must have provisions for flexibility.

Refuel gallery lines shall be reused as part of the jettison gallery to save system weight. It shall also be designed to minimise unusable fuel (Langton, Clark, Hewitt and Richards, 2009).

2.5. Jettison and defuel sub-system

CS 25.1001 (a) Fuel jettisoning system: A fuel jettisoning system must be installed on each aeroplane unless it is shown that the aeroplane meets the climb requirements of CS 25.119 and 25.121(d) at maximum take-off weight, less the actual or computed weight of fuel necessary for a 15-minute flight comprised of a take-off, go-around, and landing at the airport of departure with the aeroplane configuration, speed, power, and thrust the same as that used in meeting the applicable take-off, approach, and landing climb performance requirements of this CS–25.

2.5.1. Jettison system configuration

The fuel jettison system shall allow the crew to dump fuel overboard following an emergency in order to reduce the aircraft weight to some value at or below the maximum landing weight. The main wing tanks shall use dedicated jettison pumps, while the centre tank override pumps shall be used to support the jettison function when selected by the crew (Langton, Clark, Hewitt and Richards, 2009).

2.5.2. Jettison control

Both left and right jettison valves shall be selected independently. Following selection the jettison system shall automatically stop when the maximum landing weight is reached, or a fuel remaining target shall be selected by the crew (Langton, Clark, Hewitt and Richards, 2009).

2.5.3. Defueling system configuration

Defueling shall be accomplished using the feed pumps or by applying suction to the refuel nozzles (Langton, Clark, Hewitt and Richards, 2009).

2.5.4. Defueling control

It is desirable to disable the jettison valve during defuel to prevent inadvertent spillage (Langton, Clark, Hewitt and Richards, 2009).

2.5.5. Manifold and piping

CS 25.993 Fuel system lines and fittings: (b) each fuel line connected to components of the aeroplane between which relative motion could exist must have provisions for flexibility.

The jettison and defuel system shall share fuel lines. Opening the defuel valve via the integrated refuel panel shall connect the feed manifold to the refuel/jettison gallery (Langton, Clark, Hewitt and Richards, 2009).

Installation of the main tank jettison pump shall be arranged so that the pump inlet becomes uncovered at some predetermined safe minimum quantity (Langton, Clark, Hewitt and Richards, 2009).

2.6. APU feed sub-system

CS 25J951 General: (a) Each fuel system must be constructed and arranged to ensure a flow of fuel at a rate and pressure established for proper APU functioning under each likely operating condition, including any manoeuvre for which certification is requested and during which the APU is permitted to be in operation

CS 25J953 Fuel system independence: Each fuel system must allow the supply of fuel to the APU: (a) Through a system independent of each part of the system supplying fuel to the main engines; or (b) From the fuel supply to the main engine if provision is made for a shut-off means to isolate the APU fuel line

2.6.1. APU feed system configuration

A dedicated dc powered feed pump shall allow fuel go through the APU fuel shut-off valve to the APU at the rear of the aircraft. An isolation valve shall allow the APU feed line to be pressurized via the main engine feed line in the event of an APU pump failure (Langton, Clark, Hewitt and Richards, 2009).

2.6.2. FOD safe

System component and pump design shall consider the inlet design such that the ingestion of FOD is minimized (Langton, Clark, Hewitt and Richards, 2009).

2.6.3. Manifold and piping

CS 25J993 Fuel system lines and fittings: (b) each fuel line connected to components of the aeroplane between which relative motion could exist must have provisions for flexibility.

Fuel lines through pressurized areas shall be double walled with overboard drains suitably protected with flame arrestors (Langton, Clark, Hewitt and Richards, 2009).

2.7. Fuel measurement and management requirement

Fuel measurement and management sub-system shall include the fuel quantity indicating, fuel level detecting, fuel information management and components (pumps, valves) control functions.

2.7.1. Fuel quantity indicating

This system shall provide the following functions (Langton, Clark, Hewitt and Richards, 2009):

- determines the quantity of fuel within each fuel tank
- determines the total airplane fuel quantity
- communicates all quantities to the Airplane Information Management System (AIMS)
- communicates all quantities to the Integrated Refuel Panel
- commands refuel valves to open or close during the auto-refuel process
- provides FQIS health monitoring
- communicates all FQIS fault data to the Central Maintenance Computer System (CMCS).

2.7.2. Computing conditions

In case of the high computing device that would result in thermal problems, computing equipment shall work in air-cooled environment (Langton, Clark, Hewitt and Richards, 2009).

2.7.3. In tank system configuration

Fuel height measurement probes shall include ultrasonic fuel height measuring probes, ultrasonic velocimeter-type probe, densitometers (Langton, Clark, Hewitt and Richards, 2009).

2.7.4. Fuel management and control

The fuel management shall control of the auto-refuel process by closing the refuel valves when the correct tank quantities have been reached (Langton, Clark, Hewitt and Richards, 2009).

It shall be communicated fuel system health status to the AIMS for display on the (EICAS) (SMARTCOCKPIT.COM).

Other fuel management tasks including control of the jettison system, and de-selecting the override pumps following depletion of the centre tank shall be under the direct control of the flight crew (Langton, Clark, Hewitt and Richards, 2009).

2.7.5. System wiring

Actions shall be taken to ensure no damage to system wiring, and no incorrect breakdown voltage.

2.8. Fuel system integration

Fuel system shall support inter-system communication

The fuel information management system shall use a highly fault tolerant architecture in that even if a component or tank circuit fails, gauging of the fuel tanks is still maintained (Langton, Clark, Hewitt and Richards, 2009).

The refuel, gauging activates, and fuel information management shall under the control of a specialised fuel sub-system. Electrical power shall be provided through electrical system to this sub-system and integrated refuel panel during the refuelling process (Moir and Seabridge, 2008).

2.8.1. Fuel system interactions

Interactions with electrical system and avionics system (Langton, Clark, Hewitt and Richards, 2009):

- Refuelling valves, fuel gauging and management, integrated refuel panel shall powered by standby power from electrical system
- Important fuel system components like pumps shall have redundant design
- Signals and data between fuel quantity indicating and Avionics AIMS cabinet shall be communicated through high speed data buses

Interactions within fuel system (Langton, Clark, Hewitt and Richards, 2009):

- Fuel system control signals between integrated refuel panel, crew and fuel quantity indication shall transfer through high speed data buses. Interaction information shall include signals between fuel sensors, probes and fuel quantity indication.

2.8.2. Fuel system integration test

CS 25.952 and CS 25J952 Fuel system analysis and test: (a) Proper fuel system functioning under all probable operating conditions must be shown by analysis and those tests found necessary by the Agency. Tests, if required, must be made using the aeroplane fuel system or a test article that reproduces the operating characteristics of the portion of the fuel system to be tested.

CS 25.993 and CS 25J993 Fuel system lines and fittings: (f) each fuel line within the fuselage must be designed and installed to allow a reasonable degree of deformation and stretching without leakage.

3. Electrical system chapter

- Electrical system general technical specifications
- Electrical system general performance
- Electrical system shall generate and distribute AC and DC power to other systems, and shall be comprised of main AC and DC power, backup power, standby power, and flight controls power.

- The system operation shall be automatic. Electrical faults shall be automatically detected and isolated
- Electrical system shall provide load management and protection to ensure power is available to critical and essential equipment

3.1. Power generation sub-system

CS 25.1351 General: (b) Generating system. The generating system includes electrical power sources, main power busses, transmission cables, and associated control, regulation, and protective devices.

3.1.1. AC electrical power generation

The main AC electrical power sources shall include left and right engine integrated drive generators (IDGs), APU generator, and primary and secondary external power.

The power sources shall normally operate isolated from one another. During power source transfers on the ground (such as switching from the APU generator to an engine generator) operating sources shall be momentarily paralleled to prevent power interruption.

Each engine has an IDG. Each IDG shall have automatic control and system protection functions

The APU generator shall power either or both main buses, and can be used in flight as a replacement to an IDG source (SMARTCOCKPIT.COM).

3.1.2. DC electrical power generation

The DC electrical power generation shall use transformer-rectifier units (TRUs) to produce DC power. The TRUs shall be powered by the AC transfer buses (SMARTCOCKPIT.COM).

3.1.3. Standby, external and backup electrical power

The standby electrical system shall supply AC and DC power to selected flight instruments, communications and navigation systems, and the flight control system, if there are primary electrical power system failures. It shall consist of:

- Main battery,

- Standby inverter
- RAT generator and its associated generator control unit
- Part of TRUs

External power shall power the aircraft main buses, and redundant design shall be used in design.

Except for selection of external power, system operation shall be fully automatic. For ground operation, external power shall be connected to both AC main buses through an external power receptacle.

The backup AC electrical system shall automatically power one or both transfer buses when:

- Only one main AC generator (includes APU) is available
- Power to one or both of the main AC buses is lost
- Approach (APP) mode is selected for auto land
- The system is automatically tested after engine starts
- The system shall transfer power without interruption

The main battery shall be connected directly to the hot battery bus and shall provide standby power to other buses. The main battery charger shall normally power the hot battery bus and maintains the main battery fully charged.

The APU battery shall be connected directly to the APU battery bus and shall provide dedicated power to the APU electric starter, which is used when sufficient bleed air duct pressure is unavailable for the APU air turbine starter. The APU battery charger shall normally power the APU battery bus and maintains the APU battery fully charged (SMARTCOCKPIT.COM).

3.2. Power distribution sub-system

The electrical power distribution shall include AC and DC power distribution through buses.

3.2.1. AC electrical power distribution

AC power shall be distributed through the aircraft main buses and the ground service/handling bus.

AC main buses (SMARTCOCKPIT.COM):

- Redundant design shall be used for the following AC main buses design
- IDG shall power the AC main buses. APU shall normally power both main buses when they are not powered by any other source.
- When external power is connected, it shall power the AC main buses.
- The power transfers shall be made without interruption when the aircraft is on the ground, except when switching to external power sources
- The main buses shall power individual equipment items such as: cooling vent fan, recirculation fans, lavatory/galley fans, electric hydraulic pumps and IFE.
- Each main bus shall also power its associated buses

Ground service bus (SMARTCOCKPIT.COM):

- Redundant design shall be used in design of ground service bus
- The ground service bus shall be normally powered by the main bus. Alternate source of power for the ground service bus shall be the APU generator and external power.
- The ground service bus shall power: the main battery charger, the APU battery charger, miscellaneous cabin and system loads.

Ground handling bus (SMARTCOCKPIT.COM):

- The ground handling bus shall be powered on the ground only from the APU generator or from the primary external power source. It shall be provided for loads such as cargo handling, fuelling/defueling operations, and other equipment energized only during ground operations

3.2.2. DC electrical power distribution

TRU DC electrical power shall be distributed to various DC buses. Redundant design shall be used for this.

The TRU shall power the main DC bus, which provide a second DC power source for flight control power supply assembly (PSA), and main DC bus.

TRUs shall power the captain’s flight instrument bus and the battery bus. The captain’s flight instrument bus shall provide a second DC power source for centre flight control PSA, and first officer's flight instrument bus (SMARTCOCKPIT.COM).

3.2.3. Cable system

CS 25.689 cable systems: Each cable system must be designed so that there will be no hazardous change in cable tension throughout the range of travel under operating conditions and temperature variations.

CS 25.1353 Electrical equipment and installations: (a) Electrical equipment, controls, and wiring must be installed so that operation of any one unit or system of units will not adversely affect the simultaneous operation of any other electrical unit or system essential to the safe operation. Any electrical interference likely to be present in the aeroplane must not result in hazardous effects upon the aeroplane or its systems except under extremely remote conditions. (b) Cables must be grouped, routed and spaced so that damage to essential circuits will be minimised if there are faults in cables, particularly heavy current-carrying cables.

Fuel pumping system wiring:

- Effective means shall be provided to isolate the electrical supply for pump wire installations within tank or adjacent to the tank wall, in the event of arc faults.

FQIS Wiring:

- Effective means shall be provided to isolate the electrical supply for pump wire installations within tank or adjacent to the tank wall, in the event of arc faults.
- Additional design precautions shall be taken to prevent any unwanted stray currents from entering tanks. These precautions shall be ensured and effective even following anticipated future modifications.

3.3. Electrical system integration

The integration of electrical system shall cooperate with avionics AIMS cabinet through high speed data buses.

Loads shall be controlled and managed through electrical load management system(ELMS). This system shall provide automatically AC loads shedding by priority until the loads are within the capacity of the airplane or ground power generators. There shall be a pre-defined order for AC loads. When an additional power source becomes available or the loads decrease, ELMS shall restore power to shed systems (in the reverse order) (SMARTCOCKPIT.COM).

The ELMS shall provide power for shut-off of centre tank fuel pump during climb/cruise, and automatic pump shut-off function to prevent unintentional dry fuel pump operation, when the centre fuel tank is empty. The ELMS shall also display such information to EICAS (SMARTCOCKPIT.COM).

The ELMS architecture shall comprises power panels associated with primary and secondary power distribution.

Redundant design shall be used for power distribution and loads protect.

3.3.1. Electrical system interactions

Interactions with other user systems and control system (SMARTCOCKPIT.COM):

- Main power management function shall include: Load shed & optimization, fuel pumps & valves, Elec-Hyd Pumps, Recirc Fans, ECS Valves & Fans, Air/Ground, Probe Heat, Engine Ignition, Crew Oxygen. The main power management design shall have redundancy.
- Standby power management panel function shall include: DC Sub-system Control, Fuel Pumps & Valves, RAT Deployment, Refuel/Defuel, Standby Air/Ground, Passenger Oxygen, Fire Suppression, APU Start.
- The ELMS shall have communications to Avionics AIMS cabinet through high speed data buses.

Interactions within electrical system (SMARTCOCKPIT.COM):

- The power inputs of the ELMS shall include left and right Integrated Drive Generator (IDG), APU generator, RAT generator, backup generators and external power.

- The outputs of primary power shall use redundant design, which shall provide power to power management panel, standby power management panel and high power loads.
- Ground servicing/handing power shall get power from auxiliary power panel.

3.3.2. Electrical system integration test

Integration test method:

CS 25.1363 Electrical system tests: (a) Tests must be made to determine that the performance of the electrical supply systems meets the requirements of this CS–25 under all the appropriate normal and failure conditions. - (2) The equipment must simulate the electrical characteristics of the distribution wiring and connected loads to the extent necessary for valid test results. (b) For each flight condition that cannot be simulated adequately in the laboratory or by ground tests on the aeroplane, flight tests must be made.

Test when using external power:

CS 25.1351: (c) External power. If provisions are made for connecting external power to the aeroplane, and that external power can be electrically connected to equipment other than that used for engine starting, means must be provided to ensure that no external power supply having a reverse polarity, a reverse phase sequence (including crossed phase and neutral), open circuit line, incorrect frequency or voltage, can supply power to the aeroplane’s electrical system.

4. Environment control system (ECS) chapter

- ECS general technical specifications
- ECS general performance
- ECS shall provide air supply, air conditioning functions

4.1. Air supply sub-system

Air supply shall include the air from ram intake and from the engine bleeding.

4.1.1. Ram air intake

The ram air system shall use means to control the amount of cooling airflow through the ram air heat exchangers. Means shall be provided to help ram air flow across the heat exchangers when the aircraft is on the ground (Moir and Seabridge, 2008, 2013).

4.1.2. Engine bleed

The main source of conditioning air for aircraft shall be engine bleed from the high pressure compressor. It shall provide a source whenever the engines are running (Moir and Seabridge, 2008).

Means shall be used to restrict the flow as necessary to maintain the desired pressure for downstream systems.

There shall be means to maintain a minimum air supply pressure following on the engine pressure conditions (Moir and Seabridge, 2008).

4.1.3. Manifold and piping

CS 25.1103 Air intake system ducts and air duct system: (c) Each duct connected to components between which relative motion could exist must have means for flexibility. (d) For bleed air systems no hazard may result if a duct rupture or failure occurs at any point between the engine port and the aeroplane unit served by the bleed air.

CS 25.4138 Pressurisation and low pressure pneumatic systems: Pneumatic systems (ducting and components) served by bleed air, such as engine bleed air, air conditioning, pressurisation, engine starting and hot air ice-protection systems, which are essential for the safe operation of the aeroplane or whose failure may adversely affect any essential or critical part of the aeroplane or the safety of the occupants, must be so designed and installed as to comply the CS 25.1309 In particular account must be taken of bursting or excessive leakage.

4.2. Air conditioning sub-system

The conditioning air shall be used to provide cabin pressurisation and equipment cooling. Air conditioning packs shall be used to generate desired air for downstream system usage.

4.2.1. Temperature control

A heat exchanger shall be used to achieve the desired temperature. Means shall be provided to vary the cooling airflow to control the final air temperature of the service bleed air. The quantity of bleed air to the packs shall be controlled.

Means in the ram air system shall control the temperature of the pack outlet air (Moir and Seabridge, 2008).

4.2.2. Pressure control

The pressure of air goes in the cabin shall be controlled and maintained by means. In case of the failure of control components, means shall be used to protect the cabin from over pressurisation and under pressurisation (Moir and Seabridge, 2008).

4.2.3. Cleanliness control

In the air conditioning process, means shall be used to keep the air dry and clean (Moir and Seabridge, 2008).

4.2.4. Icing and fogging prevent

The conditioning process shall also prevent ice from forming and clogging the system, and keep the cabin from fogging at low altitudes or on ground (Moir and Seabridge, 2008).

4.2.5. Conditioned air distribution

The conditioned air shall be delivered to downstream user system, including cabin and some equipment (Moir and Seabridge, 2008).

The flow information of air distribution shall be shared and controlled by AMIS.

4.2.6. Manifold and piping

CS 25.4138 Pressurisation and low pressure pneumatic systems: Pneumatic systems (ducting and components) served by bleed air, such as engine bleed air, air conditioning, pressurisation, engine starting and hot air ice-protection systems, which are essential for the safe operation of the aeroplane or whose failure may adversely affect any essential or critical part of the aeroplane or the safety of the occupants, must be so designed and installed as to comply the CS 25.1309 In particular account must be taken of bursting or excessive leakage.

C.2 B777 functional modelling

C.2.1 2D block diagram

The B777 functions are designed in the 2D block diagram as shown in figure

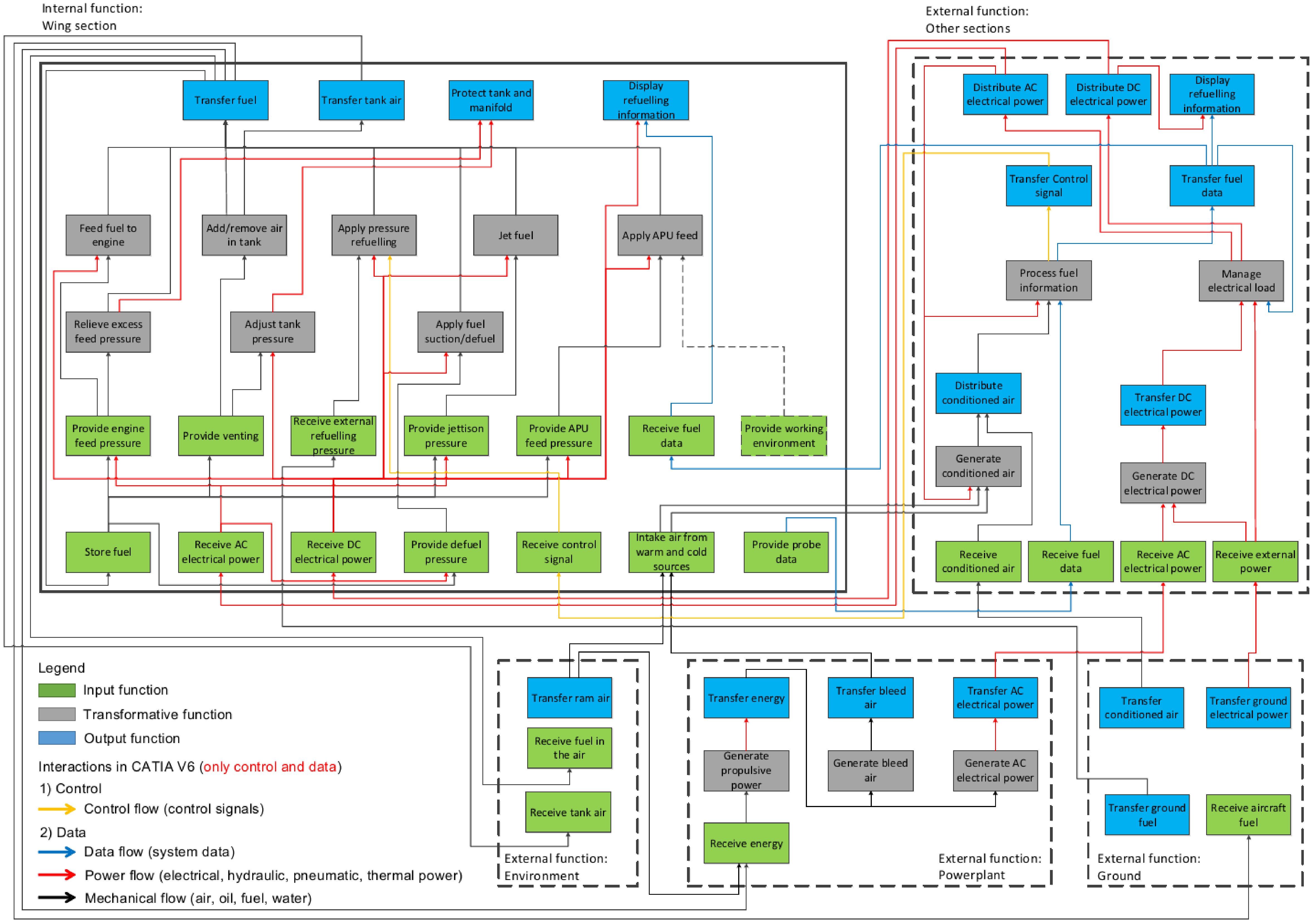
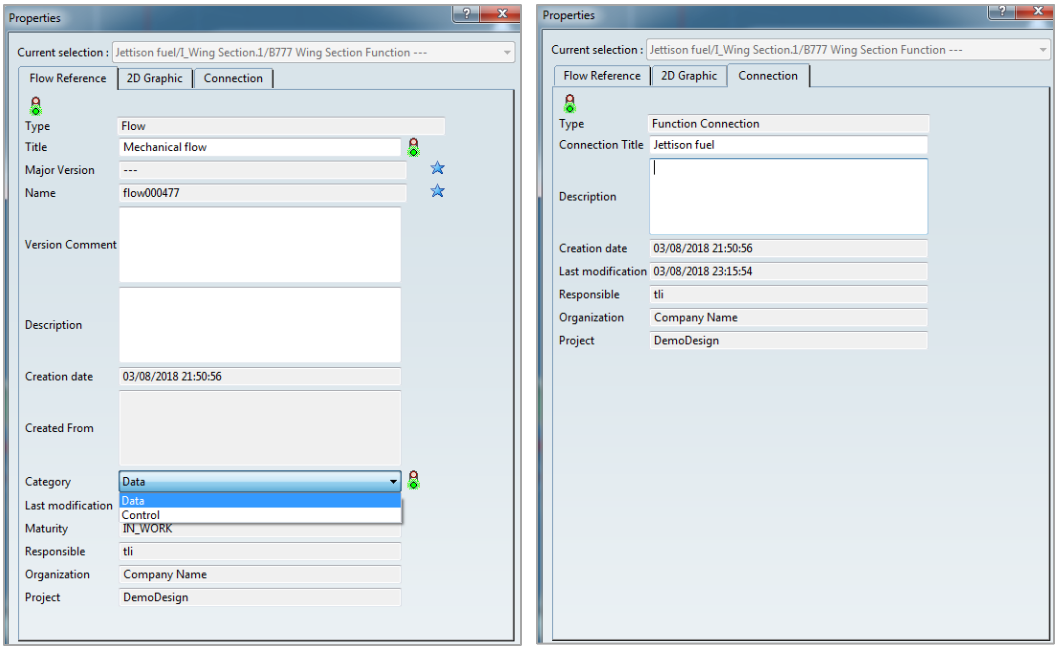


Figure C-1 2D block diagram of the B777 functional model

C.2.2 Interaction definition in functional model

In applying the interaction definition rule in table 4-1, the detailed definition property window is shown in figure C-2.



Current selection : Jettison fuel/I_Wing Section.1/B777 Wing Section Function ---
Type: Flow
Title: Mechanical flow
Major Version: ---
Name: flow000477
Version Comment:
Description:
Creation date: 03/08/2018 21:50:56
Created From:
Category: Data
Data
Control
Last modification:
Maturity: IN_WORK
Responsible: tli
Organization: Company Name
Project: DemoDesign

Current selection : Jettison fuel/I_Wing Section.1/B777 Wing Section Function ---
Type: Function Connection
Connection Title: Jettison fuel
Description:
Creation date: 03/08/2018 21:50:56
Last modification: 03/08/2018 23:15:54
Responsible: tli
Organization: Company Name
Project: DemoDesign

Figure C-2 Interaction definition example in B777 functional model

C.2.3 B777 functional modelling results

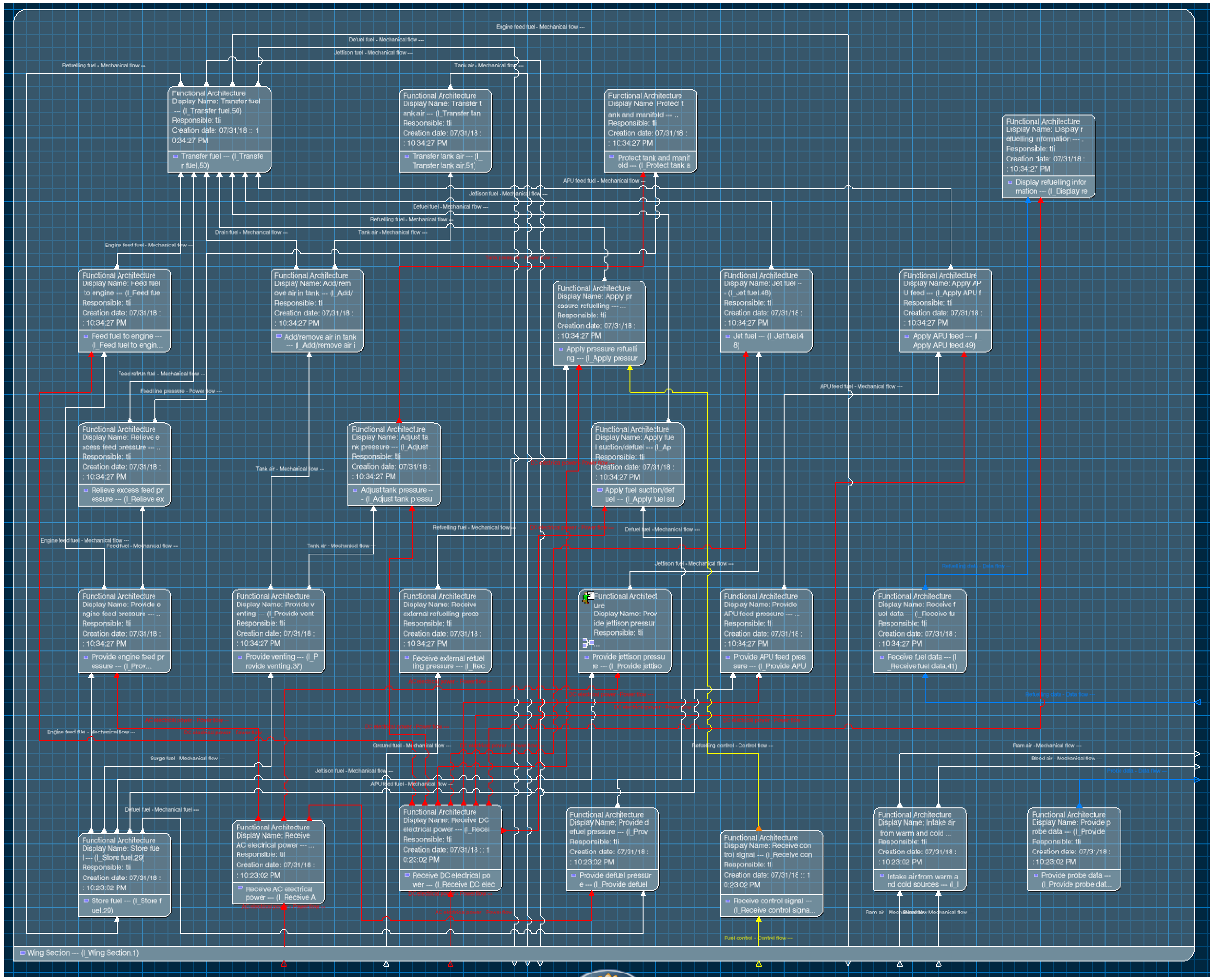


Figure C-3 B777 wing section functions in CATIA V6

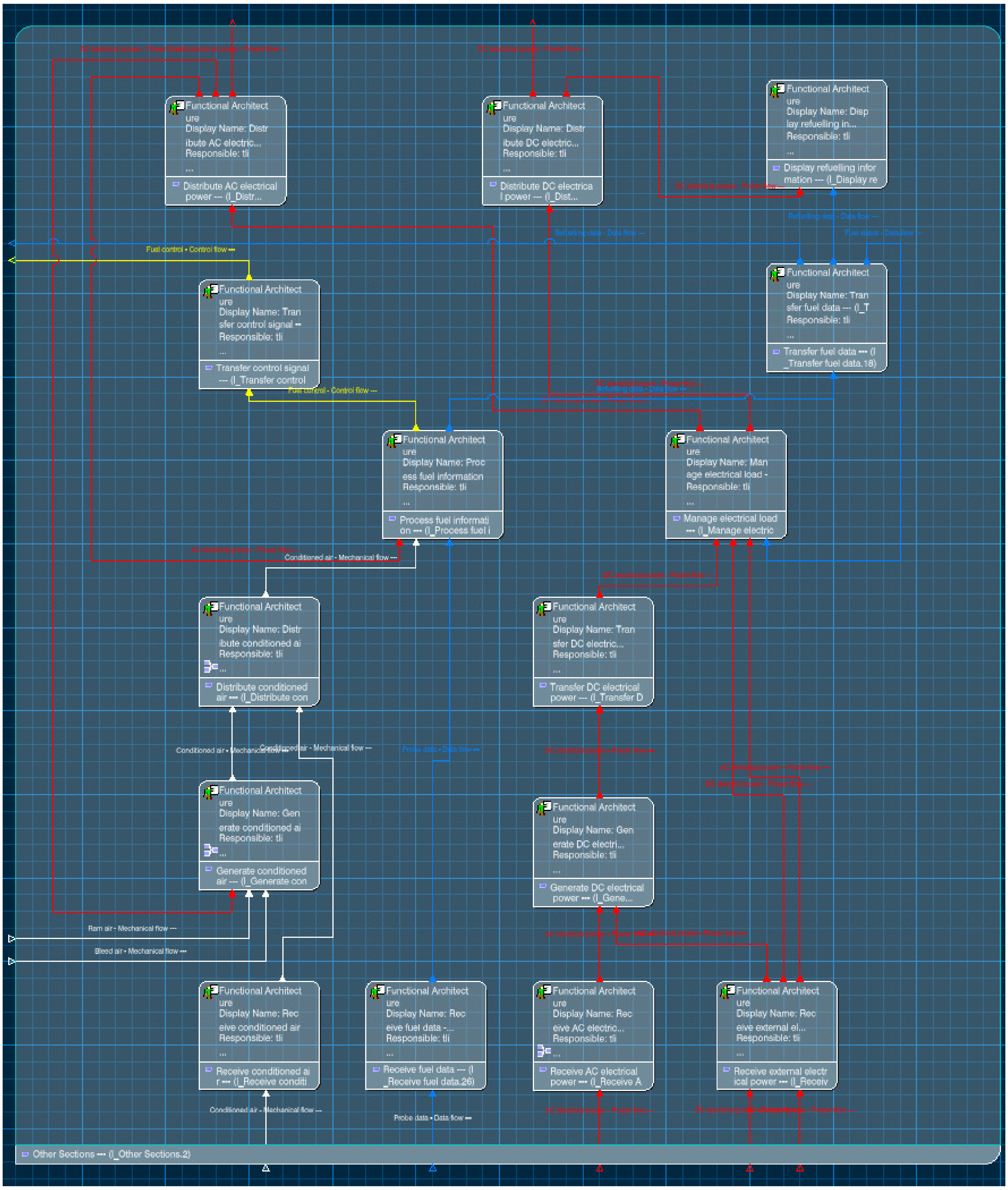


Figure C-4 B777 other sections functions

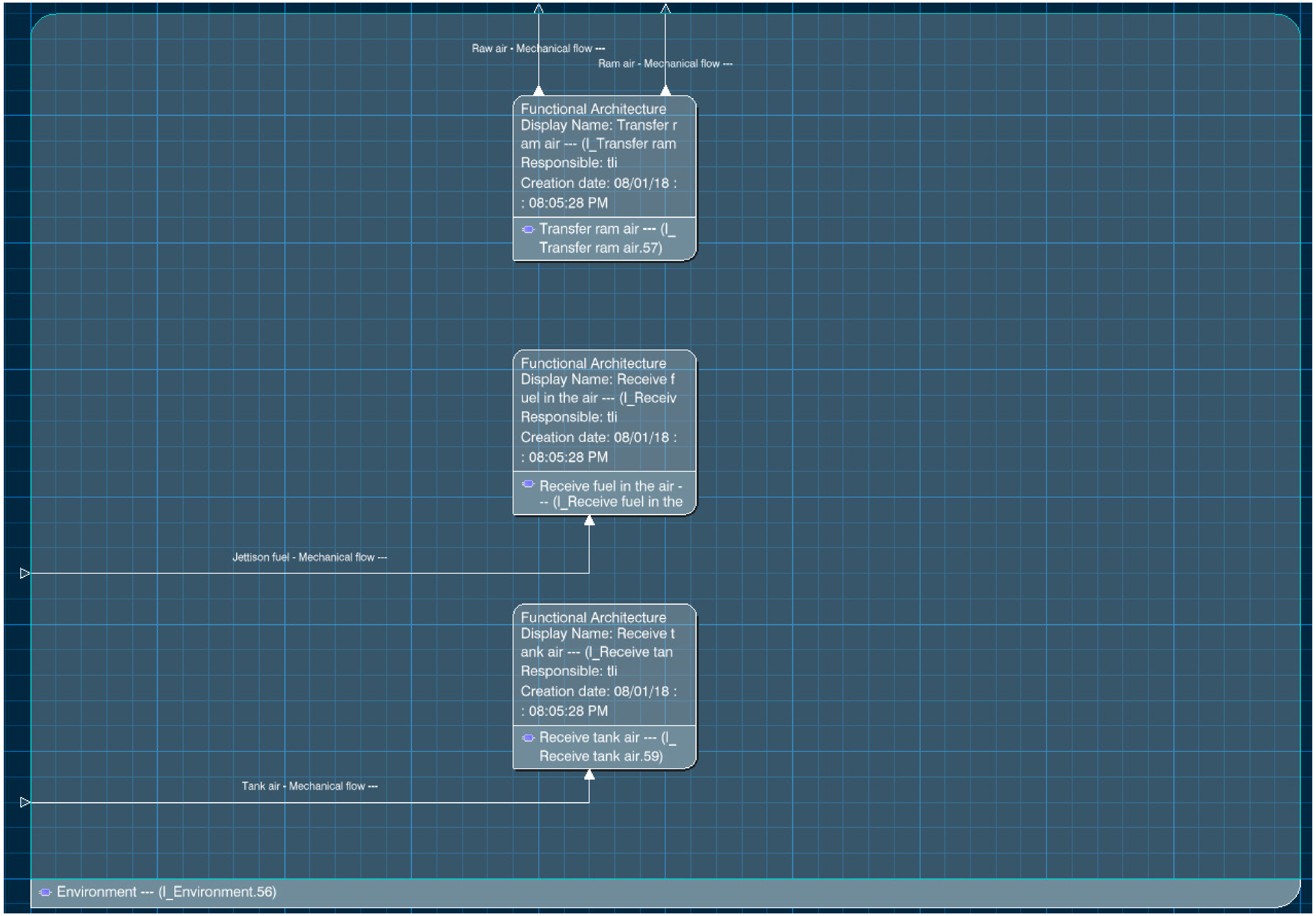


Figure C-5 B777 environment functions

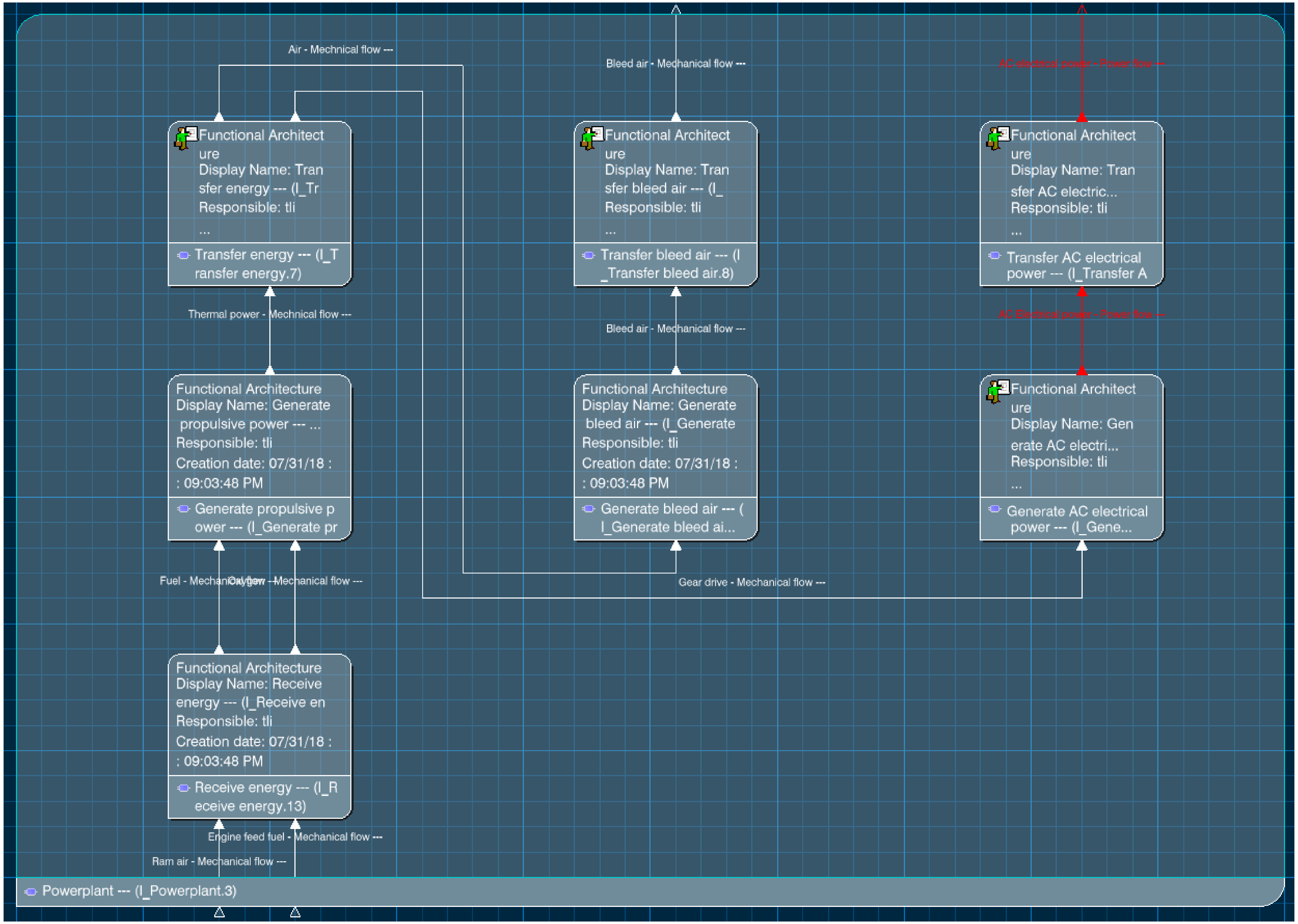


Figure C-6 B777 powerplant functions

C.3 B777 logical modelling

The B777 logical model has three levels: major system level, sub-system level and component level.

C.3.1 B777 logical model overview

Figure C-7 shows the overview of all the three levels logical models.

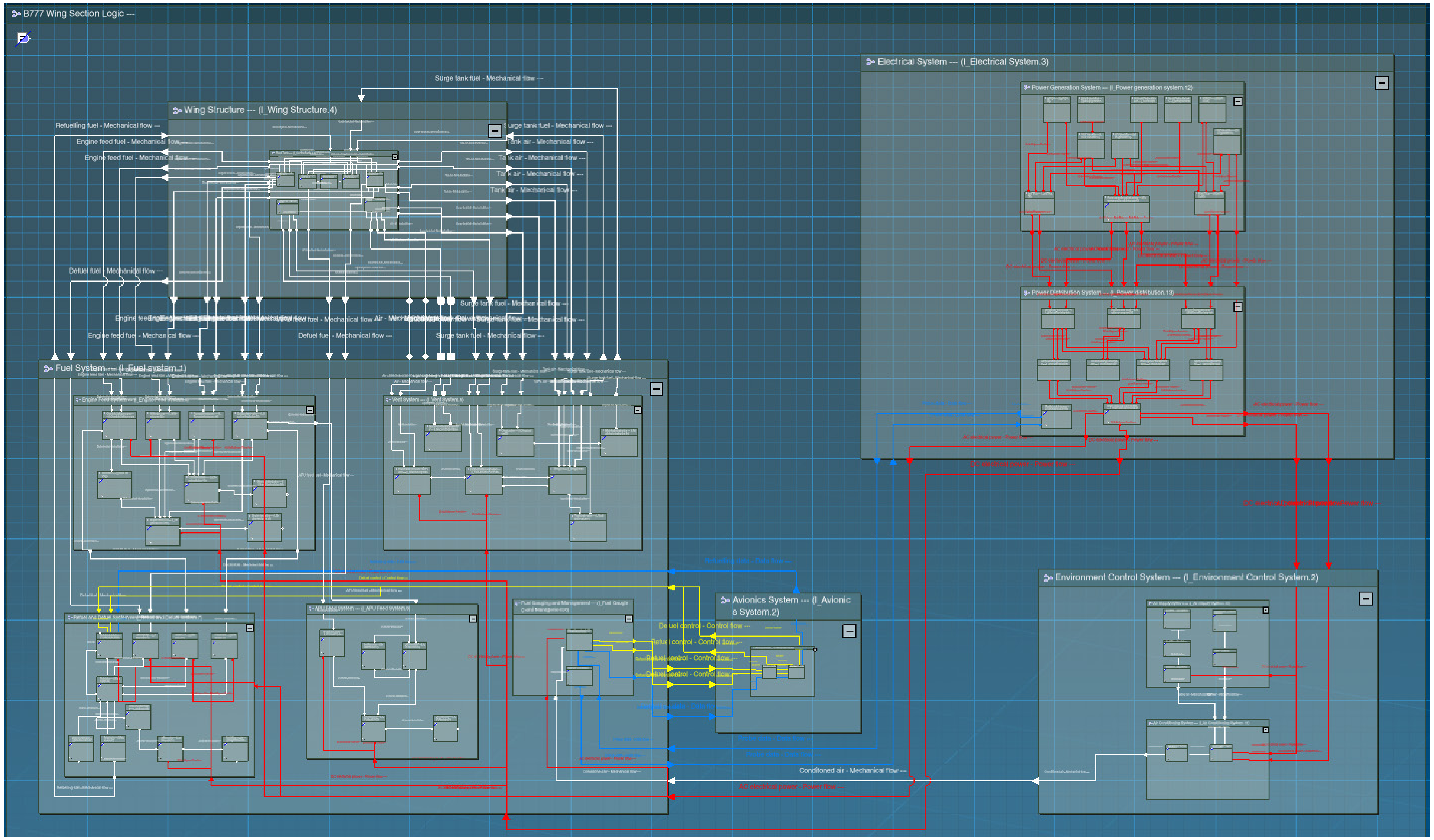


Figure C-7 B777 logical model overview including three levels

C.3.2 B777 sub-system logical models

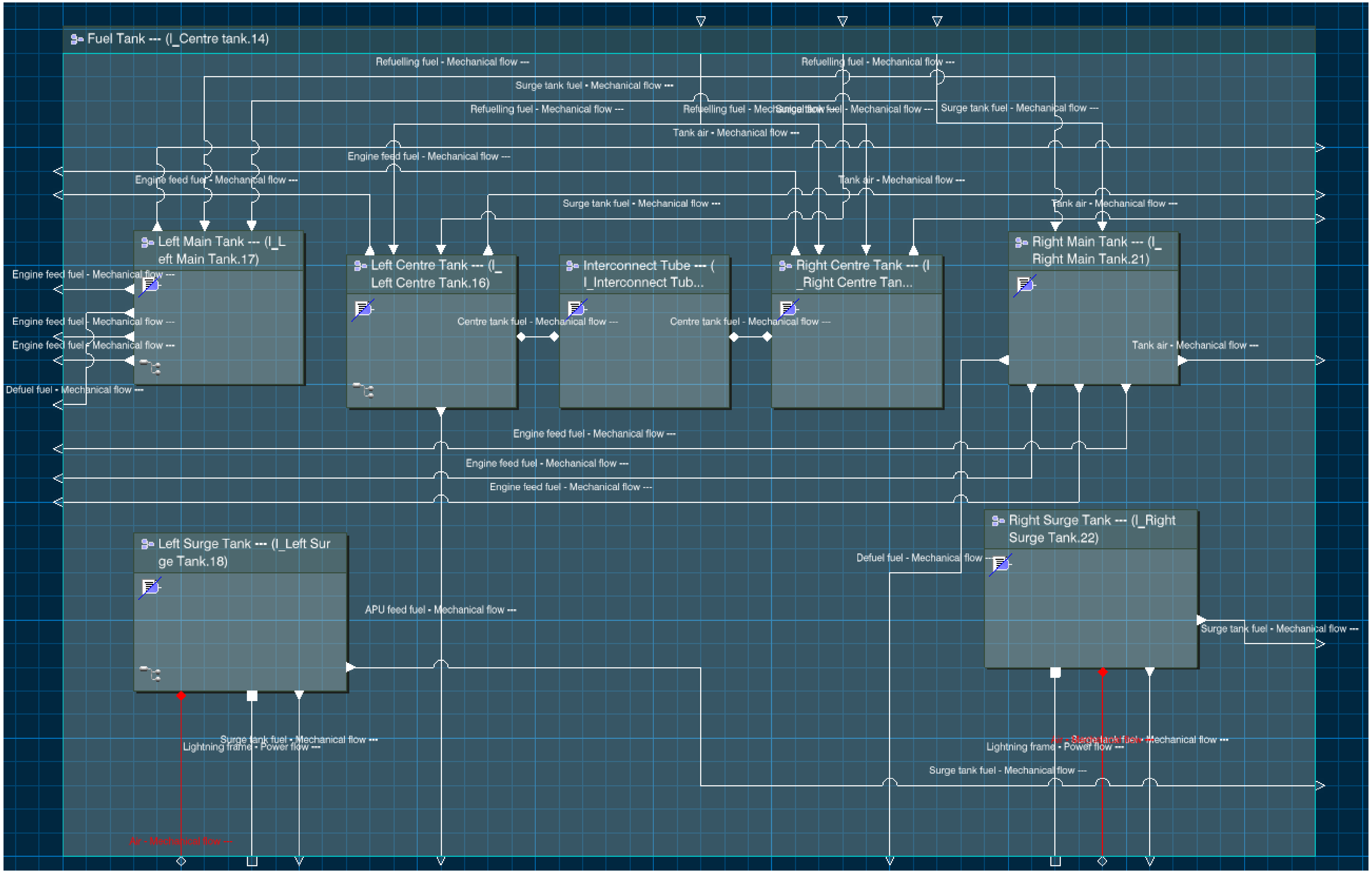


Figure C-8 B777 wing tank logical model

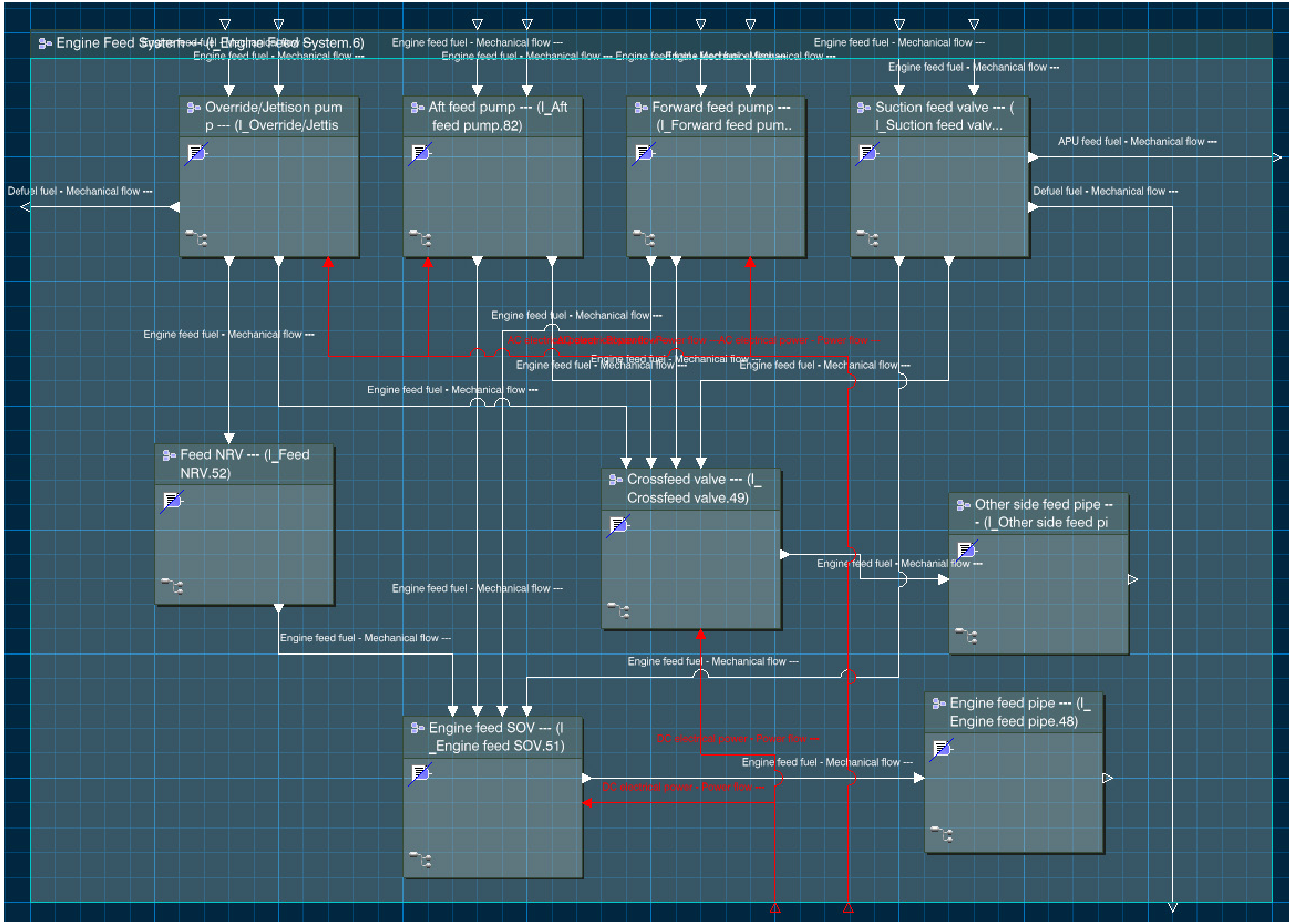


Figure C-9 B777 engine feed sub-system logical model

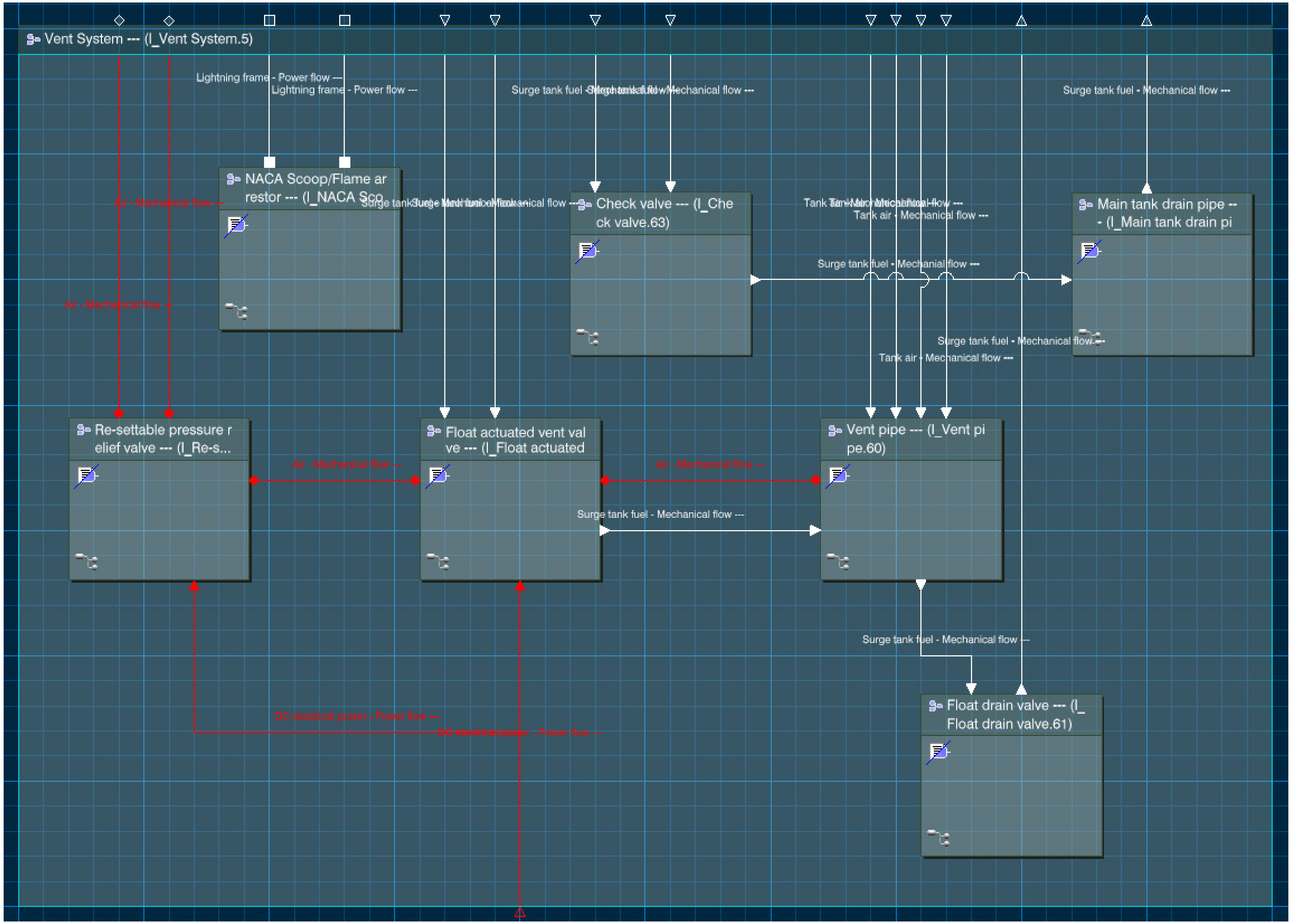


Figure C-10 B777 vent sub-system logical model

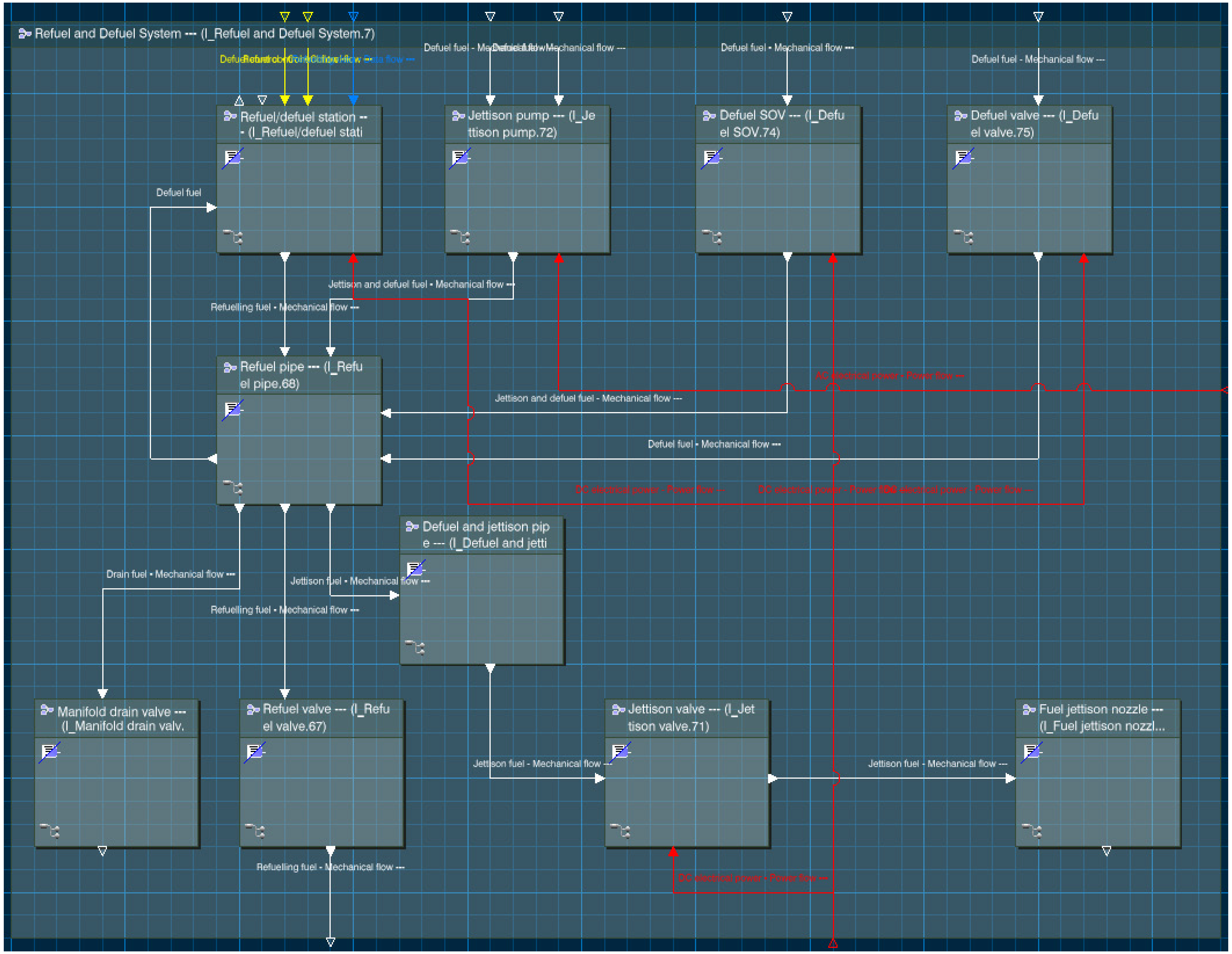


Figure C-11 B777 refuel and defuel sub-system logical model

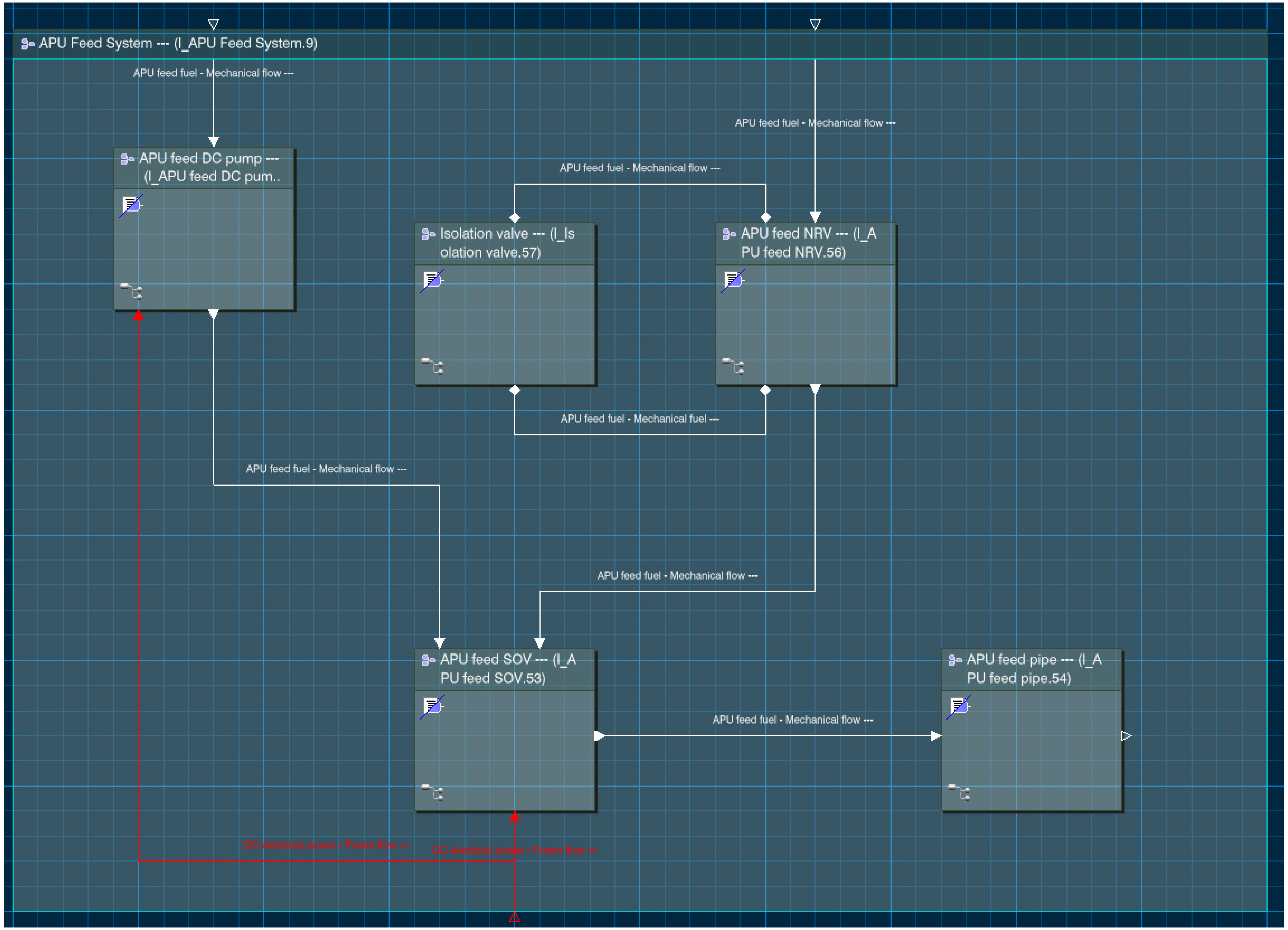


Figure C-12 B777 APU feed sub-system logical model

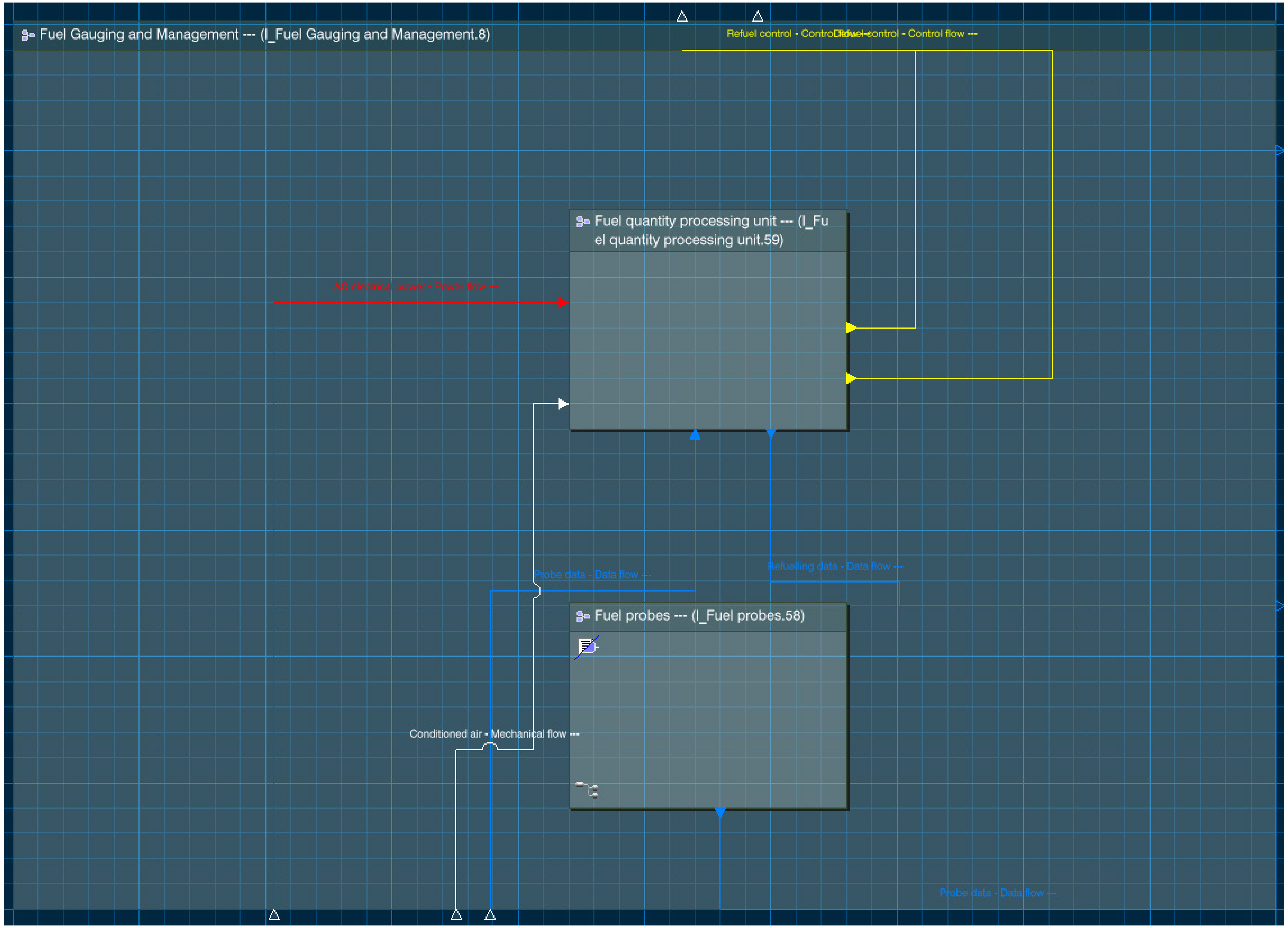


Figure C-13 B777 APU feed sub-system logical model

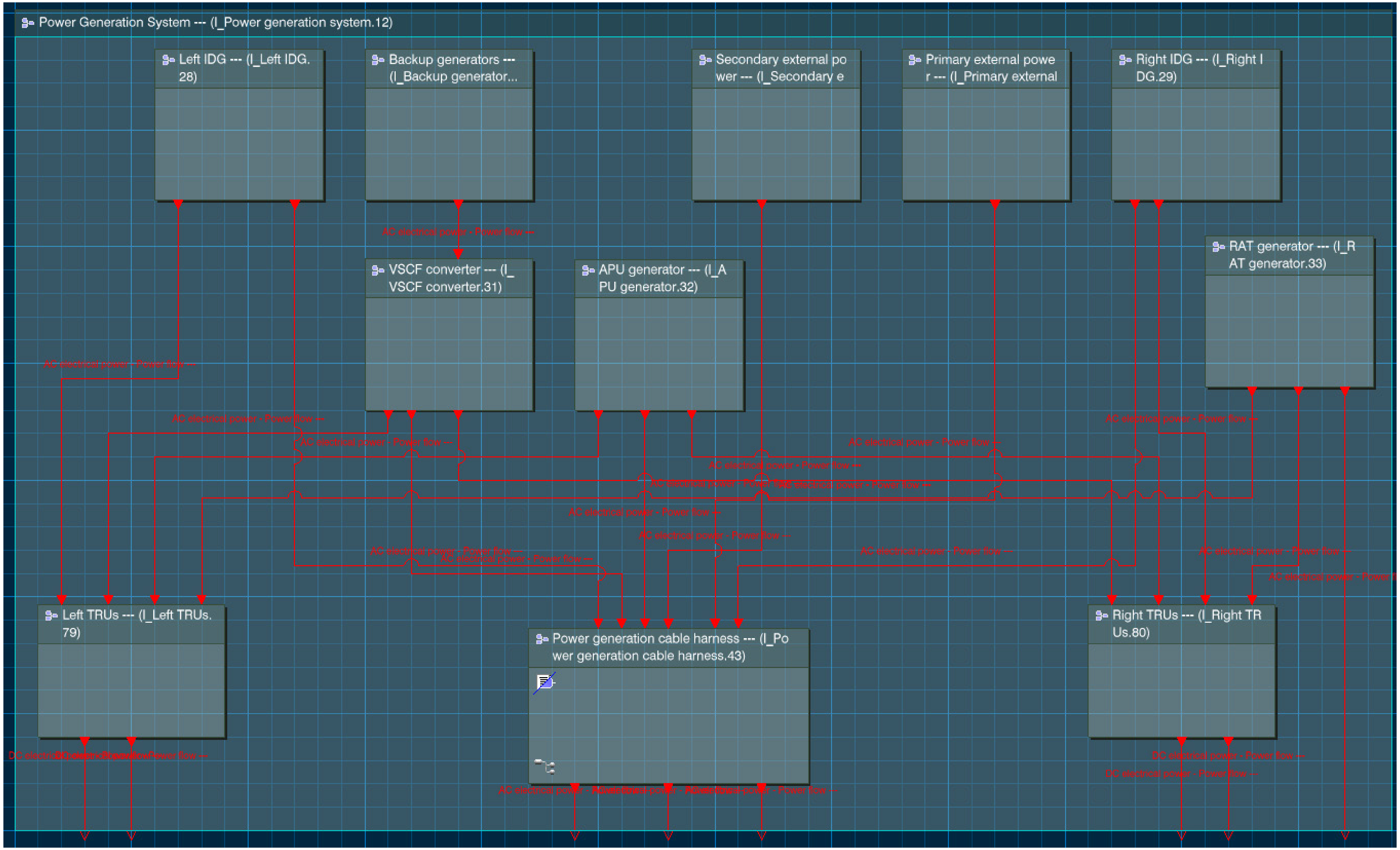


Figure C-14 B777 Power generation sub-system logical model

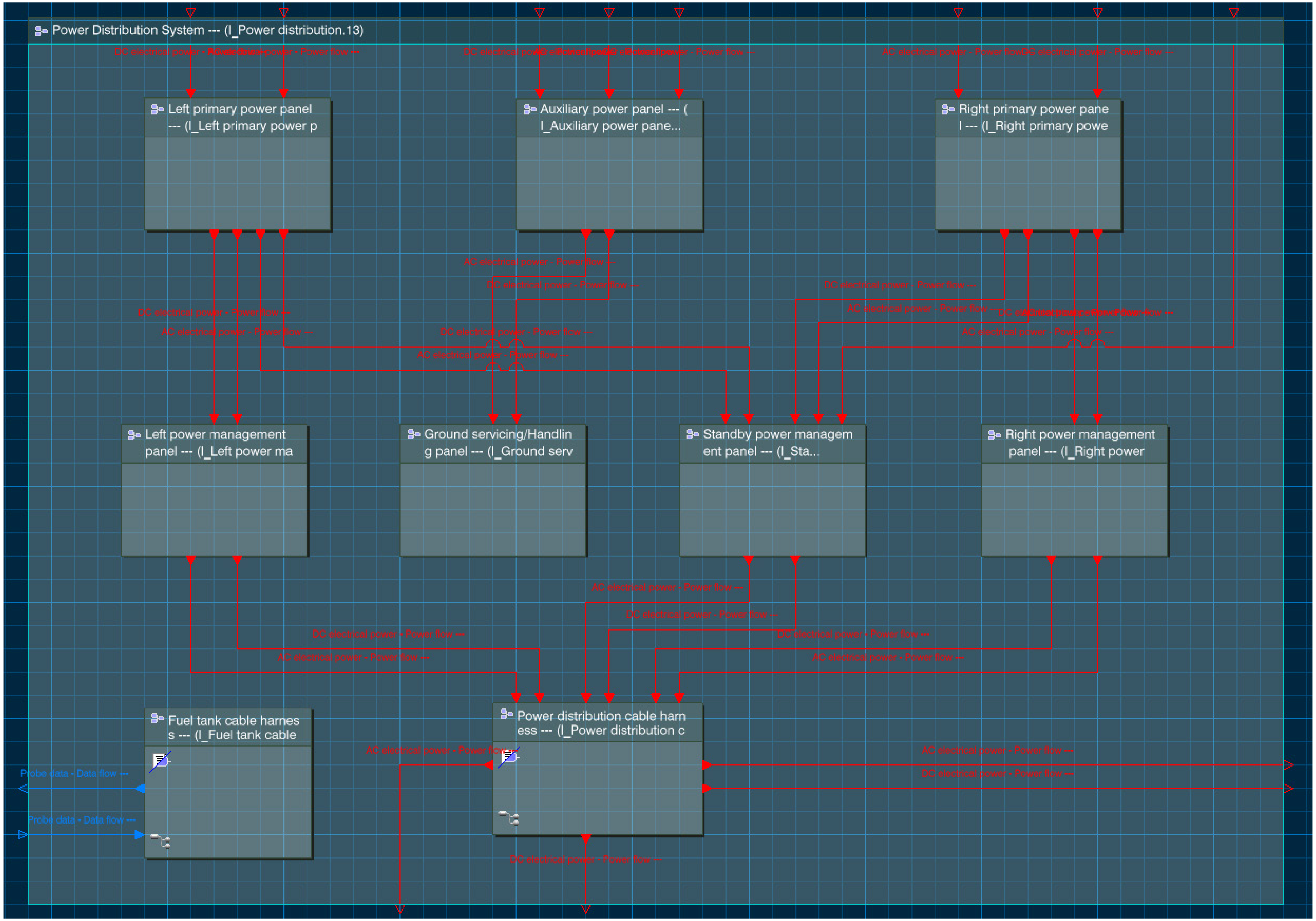


Figure C-15 B777 power distribution sub-system logical model

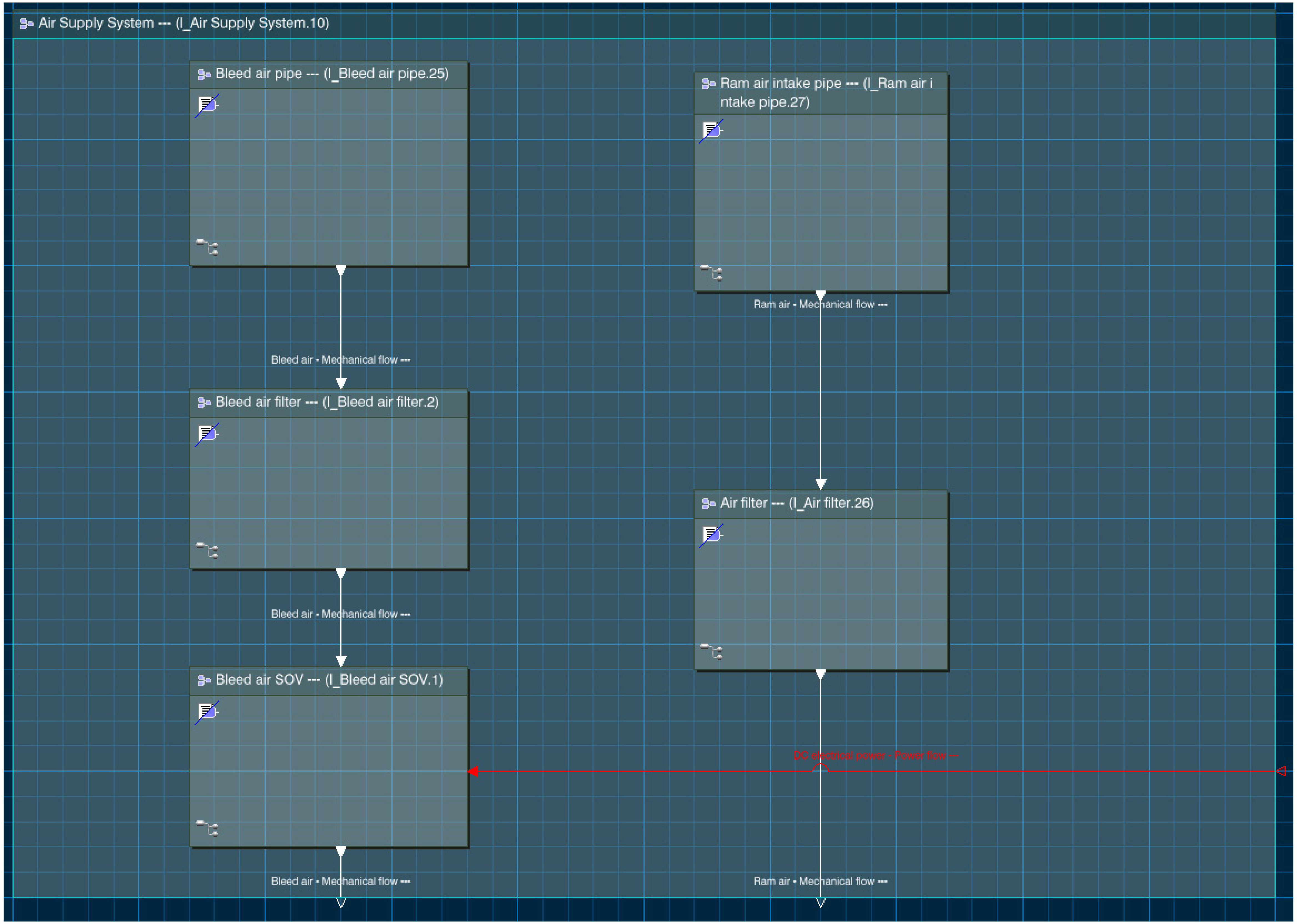


Figure C-16 B777 air supply sub-system logical model

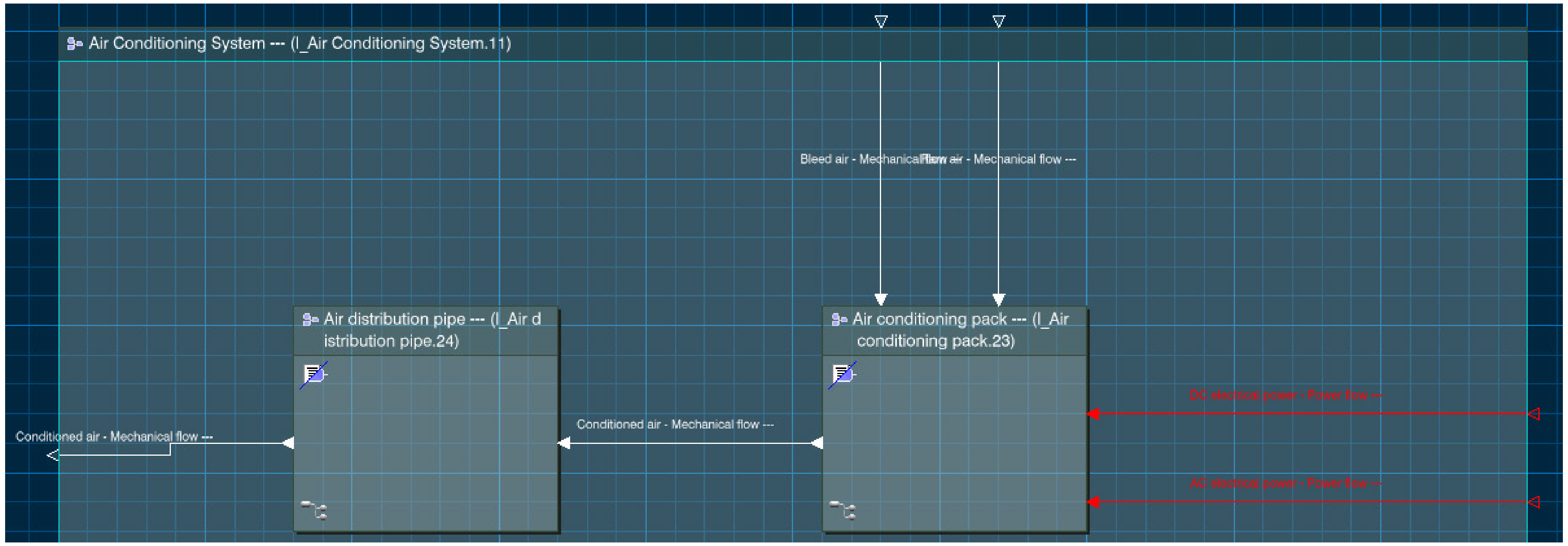


Figure C-17 B777 air conditioning sub-system logical model

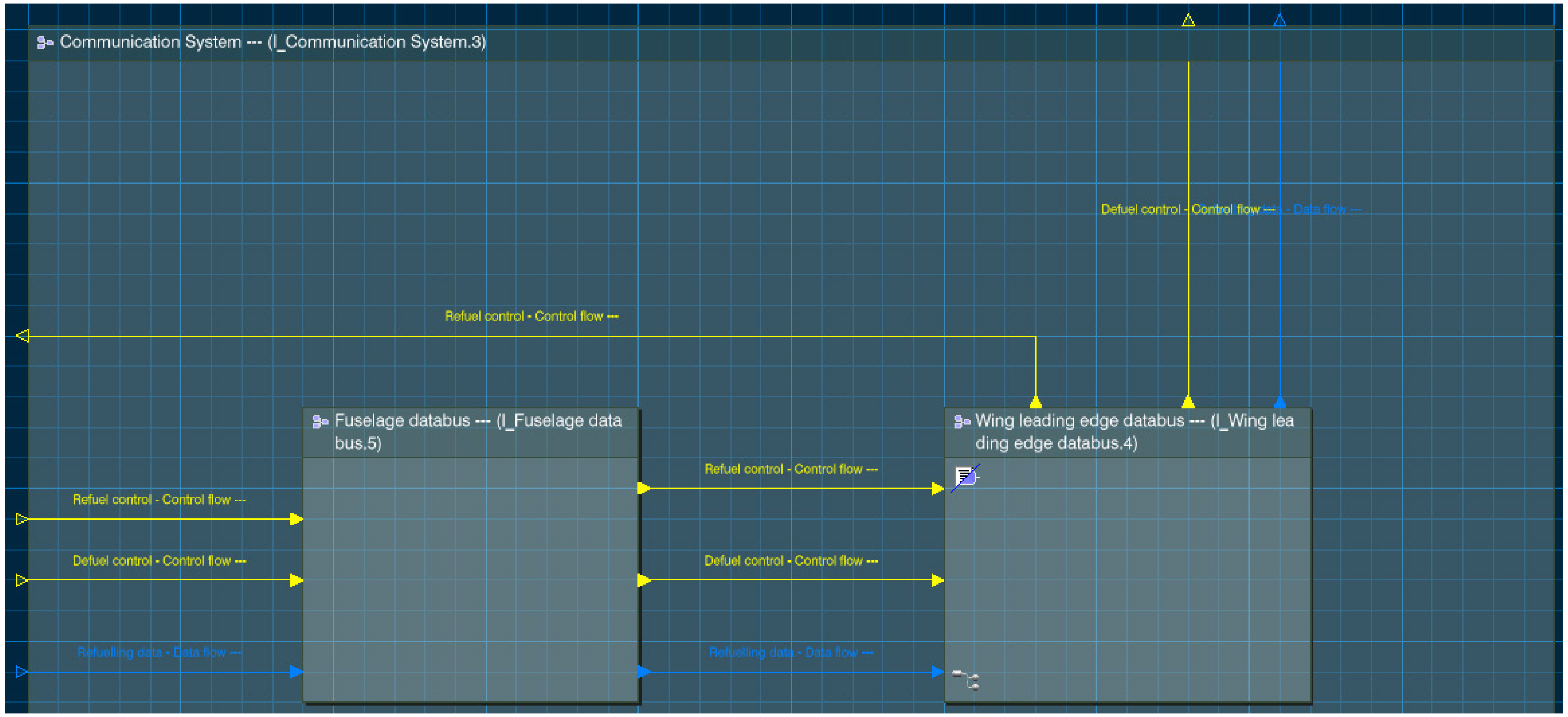


Figure C-18 B777 communication sub-system logical model

C.4 B777 assembly sequence generation results

C.4.1 Method step 2 results

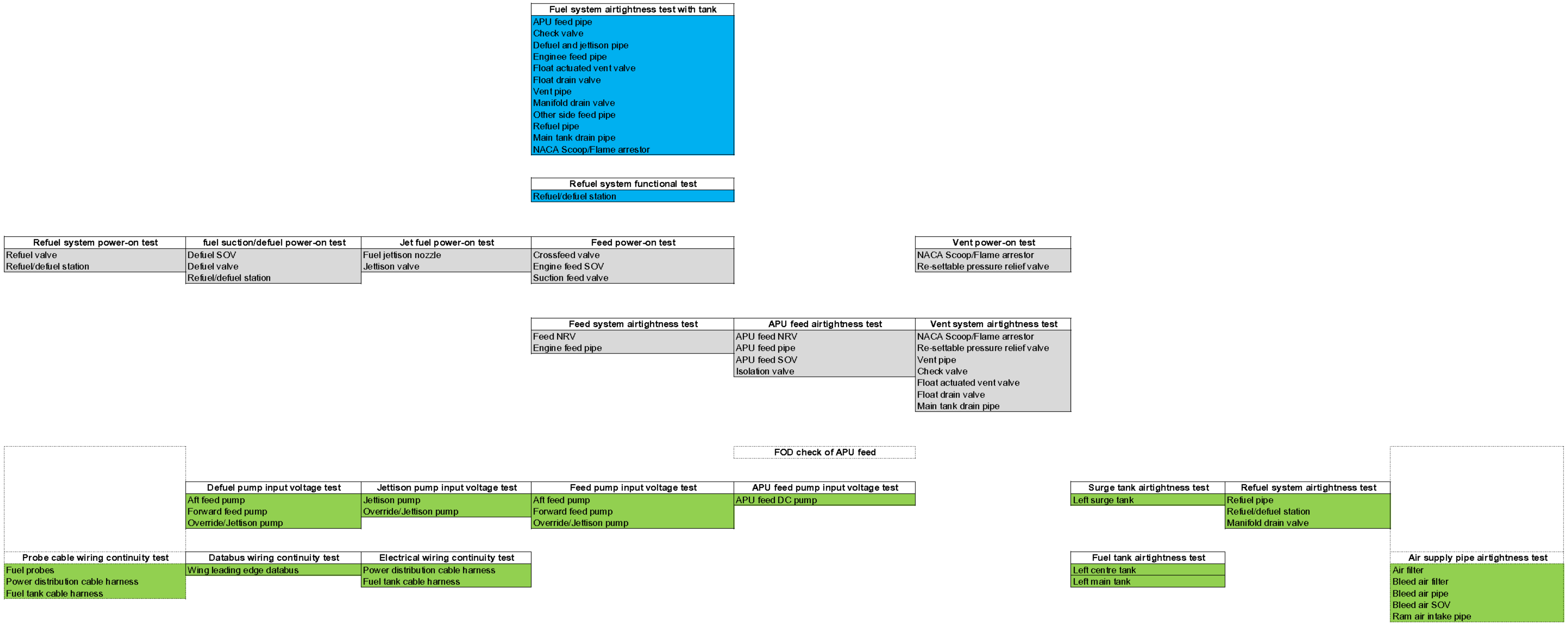


Figure C-19 B777 wing section systems test sequence associated with logical components

C.4.2 Method step 3 results

Figure C-20 shows the initial feasible installation and test sequence. The installations are all allocation from logical models to 3D physical models in the result.

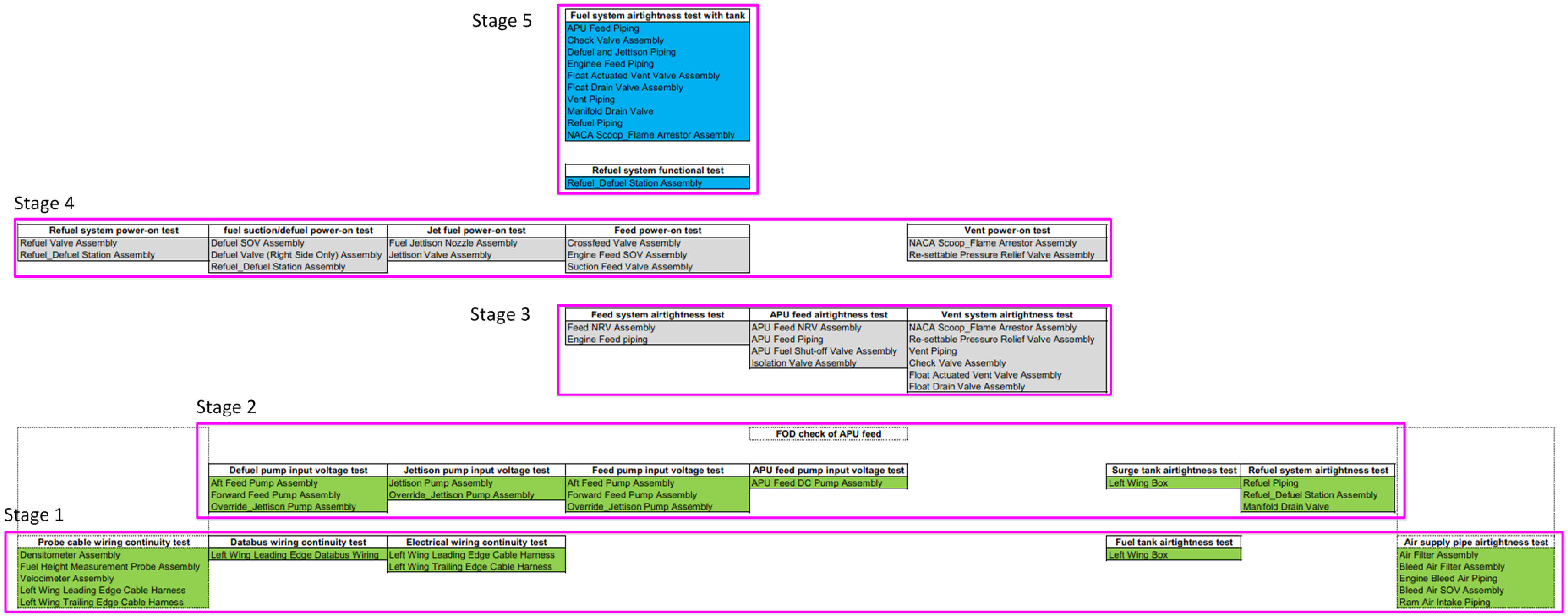


Figure C-20 B777 wing section initial feasible installation and test sequence

C.4.3 Method step 4 results

The system break check results of all the five stages are shown in table C-2

Table C-2 System break check results

Any system breaks near the structure or bay boundary for test blocking or connection?					
Stage	Test	Zone 1	Zone 2	Zone 3	Zone 4
1	Databus wiring continuity test	Yes, cable plugs	N/A	N/A	N/A
1	Electrical wiring continuity test	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs
1	Probe cable wiring continuity test	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs	Yes, cable plugs
1	Fuel tank airtightness test	N/A	N/A	Yes, structural connectors	Yes, structural connectors
1	Air supply pipe airtightness test	Yes, pipe ends and the breaks at wing root, and engine pipe connectors	N/A	N/A	N/A
2	Defuel pump input voltage test	N/A	Yes, cable plugs	N/A	N/A
2	Jettison pump input voltage test	N/A	Yes, cable plugs	N/A	N/A
2	Feed pump input voltage test	N/A	Yes, cable plugs	N/A	N/A
2	APU feed pump input voltage test	N/A	Yes, cable plugs	N/A	N/A

Table C-2 (continued)

2	Surge tank airtightness test	N/A	N/A	N/A	Yes, connectors on surge tank, and valve open ends on surge tank floor
2	Refuel system airtightness test	Yes, connectors at refuel/defuel station	Yes, jettison nozzle ends	Yes, manifold drain valve, and wing root pipe breaks	Yes, connectors on surge tank structure
3	Feed system airtightness test	N/A	Yes, feed pump pipe connectors on structure	Yes, wing root pipe breaks	Yes, tank floor engine feed connector
3	APU feed airtightness test	N/A	Yes, APU feed pump pipe connectors on structure	Yes, win root pipe breaks	Yes, pipe connector on dry bay structure
3	Vent system airtightness test	N/A	N/A	Yes, wing root pipe breaks	Yes, pipe connectors on surge tank structure
4	Refuel system power-on test	Yes, cable plugs	Yes, cable plugs	Yes, cable connectors on tank structure	Yes, cable connectors on tank structure
4	Fuel suction/defuel power-on test	Yes, cable plugs	Yes, cable plugs	Yes, cable connectors on tank structure	N/A
4	Jet fuel power-on test	N/A	Yes, cable plugs	N/A	Yes, cable plugs
4	Feed power-on test	N/A	Yes, cable plugs	Yes, cable connectors on tank structure	Yes, cable connectors on tank structure

Table C-2 (continued)

4	Vent power-on test	N/A	Yes, cable plugs	N/A	Yes, cable connectors on tank structure
5	Refuel system functional test	Yes, cable plugs	Yes, cable plugs	Yes, cable connectors on tank structure	Yes, cable connectors on tank structure
5	Fuel system airtightness test with tank	Yes, connectors on at refuel/defuel station, engine pipe connector	Yes, jettison pipe end	Yes, manifold drain valve, and wing root pipe breaks	Yes, valve open ends on surge tank floor

The test related accessibility path analysis results are shown in table C-3.

Table C-3 Test related accessibility path analysis results

Stage	Test	Analysis of current assembly process: can current test sequence satisfy aircraft system installation/uninstallation path?
1	Databus wiring continuity test	Yes, databus cable harnesses can be installed first in this zone before electrical cable harness. The wiring continuity test can be done in parallel.
1	Electrical wiring continuity test	Yes, electrical cable harness can be installed with tank cable. The wiring continuity test can be done in parallel.
1	Probe cable wiring continuity test	Yes, probe cable harness can be installed with electrical cable. The wiring continuity test can be done in parallel.
1	Fuel tank airtightness test	Yes. But testing fuel tank airtightness at this point means the tank structure is closed. System tests and related installations/uninstallations are accessed through access panels. The path space may not be sufficient. Need to be reviewed in later development stage once more system physical design information is available.
1	Air supply pipe airtightness test	Yes. There are no technical constraints at input functional test level for installation of air supply pipe. The installation and test can be used as work load balancing in later stage.
2	Defuel pump input voltage test	Yes. Fuel pumps can be installed after the electrical cable harness wiring. Test point on the cable plugs is accessible.

Table C-3 (continued)

2	Jettison pump input voltage test	Yes. Fuel pumps can be installed after the electrical cable harness wiring. Test point on the cable plugs is accessible.
2	Feed pump input voltage test	Yes. Fuel pumps can be installed after the electrical cable harness wiring. Test point on the cable plugs is accessible.
2	APU feed pump input voltage test	Yes. Fuel pumps can be installed after the electrical cable harness wiring. Test point on the cable plugs is accessible.
2	Surge tank airtightness test	Yes. Testing surge tank airtightness at this point means the tank structure is closed. System tests and related installations/uninstallations are finished through access panels. The path space may not be sufficient. Need to be reviewed at later development stage once more system physical design information is available.
2	Refuel system airtightness test	Yes, but some blocking points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again.
3	Feed system airtightness test	Yes, but some blocking points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again. Engine feed SOV can be switched off through specialised ground device.
3	APU feed airtightness test	Yes, but some blocking points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again. Engine feed SOV can be switched off through specialised ground device.
3	Vent system airtightness test	Yes, but some blocking points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again.
4	Refuel system power-on test	Yes, but some cable plug connection points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again.
4	Fuel suction/defuel power-on test	Yes, but some cable plug connection points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again.
4	Jet fuel power-on test	Yes, but some cable plug connection points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again.

Table C-3 (continued)

4	Feed power-on test	Yes, but some cable plug connection points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again.
4	Vent power-on test	Yes, but some cable plug connection points in the tank need to be done through access planes. Once more detailed system layout design is available, this should be reviewed again.
5	Refuel system functional test	Yes, at this point the refuel system is ready to be run the loop under the driven of specialised ground equipment. Test only need to verify the information displayed in the refuel/defuel station(integrated refuel plane)
5	Fuel system airtightness test with tank	Yes, blocking points are at the major mating area and surface which are accessible for operations and equipment connection.

C.5 B777 requirement traceability results

C.5.1 Tracing in requirements decomposition process

The extracted B777 requirement traceability in table C-4 is arranged as the following manner: PLM requirement name – Requirement name – Functional model – Logical component – Physical item.

Table C-4 B777 case study requirement traceability links

R-0000060 A
- **Fuel tank location**
  - Store fuel --- (I_Store fuel.29)
    - **Left Centre Tank --- (I_Left Centre Tank.16)**
      - Left Wing Box
    - **Left Main Tank --- (I_Left Main Tank.17)**
      - Left Wing Box

R-0000061 A
- **Fuel tank installation**
  - Store fuel --- (I_Store fuel.29)
    - **Left Centre Tank --- (I_Left Centre Tank.16)**
      - Left Wing Box
    - **Left Main Tank --- (I_Left Main Tank.17)**
      - Left Wing Box

R-0000062 A

Table C-4 (continued)

- **Fuel tank test**
  - Store fuel --- (I_Store fuel.29)
    - **Left Centre Tank --- (I_Left Centre Tank.16)**
      - Left Wing Box
    - **Left Main Tank --- (I_Left Main Tank.17)**
      - Left Wing Box

R-0000063 A

- **Feed pumping**
  - Provide defuel pressure --- (I_Provide defuel pressure.32)
    - **Aft feed pump --- (I_Aft feed pump.82)**
      - Aft Feed Pump Assembly
    - **Forward feed pump --- (I_Forward feed pump.46)**
      - Forward Feed Pump Assembly
    - **Override/Jettison pump --- (I_Override/Jettison pump.47)**
      - Override_Jettison Pump Assembly
  - Provide engine feed pressure --- (I_Provide engine feed pressure.36)
    - **Aft feed pump --- (I_Aft feed pump.82)**
      - Aft Feed Pump Assembly
    - **Forward feed pump --- (I_Forward feed pump.46)**
      - Forward Feed Pump Assembly
    - **Override/Jettison pump --- (I_Override/Jettison pump.47)**
      - Override_Jettison Pump Assembly
  - Receive AC electrical power --- (I_Receive AC electrical power.30)
    - **Power distribution cable harness --- (I_Power distribution cable harness.45)**
      - Left Wing Leading Edge Cable Harness
      - Left Wing Trailing Edge Cable Harness

R-0000064 A

- **Cross-feed**
  - Feed fuel to engine --- (I_Feed fuel to engine.43)
    - **Crossfeed valve --- (I_Crossfeed valve.49)**
      - Crossfeed Valve Assembly
    - **Engine feed SOV --- (I_Engine feed SOV.51)**
      - Engine Feed SOV Assembly
    - **Suction feed valve --- (I_Suction feed valve.50)**
      - Suction Feed Valve Assembly
  - Receive DC electrical power --- (I_Receive DC electrical power.31)
    - **Power distribution cable harness --- (I_Power distribution cable harness.45)**
      - Left Wing Leading Edge Cable Harness
      - Left Wing Trailing Edge Cable Harness

R-0000065 A

- **Over pressure protection**
  - Relieve excess feed pressure --- (I_Relieve excess feed pressure.42)
    - **Feed NRV --- (I_Feed NRV.52)**
      - Feed NRV Assembly

Table C-4 (continued)

R-0000066 A

- **Feed manifold and piping**
  - Transfer fuel --- (I_Transfer fuel.50)
    - **Engine feed pipe --- (I_Engine feed pipe.48)**
      - Enginee Feed Piping
    - **Other side feed pipe --- (I_Other side feed pipe.83)**
      - Enginee Feed Piping

R-0000067 A

- **Surge tank configuration**
  - Add/remove air in tank --- (I_Add/remove air in tank.45)
    - **NACA Scoop/Flame arrestor --- (I_NACA Scoop/Flame arrestor.65)**
      - NACA Scoop_Flame Arrestor Assembly
    - **Re-settable pressure relief valve --- (I_Re-settable pressure relief valve.64)**
      - Re-settable Pressure Relief Valve Assembly
  - Provide venting --- (I_Provide venting.37)
    - **Left Surge Tank --- (I_Left Surge Tank.18)**
      - Left Wing Box

R-0000068 A

- **Surge tank configuration**
  - Adjust tank pressure --- (I_Adjust tank pressure.44)
    - **NACA Scoop/Flame arrestor --- (I_NACA Scoop/Flame arrestor.65)**
      - NACA Scoop_Flame Arrestor Assembly
    - **Re-settable pressure relief valve --- (I_Re-settable pressure relief valve.64)**
      - Re-settable Pressure Relief Valve Assembly

R-0000069 A

- **Vent fuel drain**
  - Transfer fuel --- (I_Transfer fuel.50)
    - **Check valve --- (I_Check valve.63)**
      - Check Valve Assembly
    - **Float drain valve --- (I_Float drain valve.61)**
      - Float Drain Valve Assembly
    - **Main tank drain pipe --- (I_Main tank drain pipe.84)**
      - Vent Piping

R-0000070 A

- **Vent manifold and piping**
  - Protect tank and manifold --- (I_Protect tank and manifold.52)
    - **NACA Scoop/Flame arrestor --- (I_NACA Scoop/Flame arrestor.65)**
      - NACA Scoop_Flame Arrestor Assembly
  - Transfer fuel --- (I_Transfer fuel.50)
    - **Check valve --- (I_Check valve.63)**
      - Check Valve Assembly
    - **Float drain valve --- (I_Float drain valve.61)**
      - Float Drain Valve Assembly
    - **Main tank drain pipe --- (I_Main tank drain pipe.84)**

Table C4 (continued)

- Vent Piping
- **Vent pipe --- (I_Vent pipe.60)**
  - Vent Piping
- Transfer tank air --- (I_Transfer tank air.51)
  - **Float actuated vent valve --- (I_Float actuated vent valve.62)**
    - Float Actuated Vent Valve Assembly
  - **Vent pipe --- (I_Vent pipe.60)**
    - Vent Piping

R-0000071 A

- **Refuelling system configuration**
  - Apply pressure refuelling --- (I_Apply pressure refuelling.46)
    - **Refuel valve --- (I_Refuel valve.67)**
      - Refuel Valve Assembly
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly
  - Display refuelling information --- (I_Display refuelling information.53)
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly
  - Receive DC electrical power --- (I_Receive DC electrical power.31)
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly
  - Receive external refuelling pressure --- (I_Receive external refuelling pressure.38)
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly

R-0000072 A

- **Refuelling control**
  - Apply pressure refuelling --- (I_Apply pressure refuelling.46)
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly

R-0000073 A

- **Weight control**
  - Apply pressure refuelling --- (I_Apply pressure refuelling.46)
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly

R-0000074 A

- **Refuel manifold and piping**
  - Transfer fuel --- (I_Transfer fuel.50)
    - **Manifold drain valve --- (I_Manifold drain valve.69)**
      - Manifold Drain Valve
    - **Refuel pipe --- (I_Refuel pipe.68)**
      - Refuel Piping

R-0000075 A

- **Jettison system configuration**
  - Provide jettison pressure --- (I_Provide jettison pressure.39)

Table C-4 (continued)

- **Jettison pump --- (I_Jettison pump.72)**
  - Jettison Pump Assembly
- **Override/Jettison pump --- (I_Override/Jettison pump.47)**
  - Override_Jettison Pump Assembly

R-0000076 A

- **Jettison control**
  - Jet fuel --- (I_Jet fuel.48)
    - **Fuel jettison nozzle --- (I_Fuel jettison nozzle.66)**
      - Fuel Jettison Nozzle Assembly
    - **Jettison pump --- (I_Jettison pump.72)**
      - Jettison Pump Assembly
    - **Jettison valve --- (I_Jettison valve.71)**
      - Jettison Valve Assembly

R-0000077 A

- **Defueling system configuration**
  - Apply fuel suction/defuel --- (I_Apply fuel suction/defuel.47)
    - **Defuel SOV --- (I_Defuel SOV.74)**
      - Defuel SOV Assembly
    - **Defuel valve --- (I_Defuel valve.75)**
      - Defuel Valve (Right Side Only) Assembly
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly
  - Provide defuel pressure --- (I_Provide defuel pressure.32)
    - **Aft feed pump --- (I_Aft feed pump.82)**
      - Aft Feed Pump Assembly
    - **Forward feed pump --- (I_Forward feed pump.46)**
      - Forward Feed Pump Assembly
    - **Override/Jettison pump --- (I_Override/Jettison pump.47)**
      - Override_Jettison Pump Assembly

R-0000078 A

- **Defueling control**
  - Apply fuel suction/defuel --- (I_Apply fuel suction/defuel.47)
    - **Defuel SOV --- (I_Defuel SOV.74)**
      - Defuel SOV Assembly
    - **Defuel valve --- (I_Defuel valve.75)**
      - Defuel Valve (Right Side Only) Assembly
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly

R-0000079 A

- **Jettison and defuel manifold and piping**
  - Transfer fuel --- (I_Transfer fuel.50)
    - **Defuel and jettison pipe --- (I_Defuel and jettison pipe.73)**
      - Defuel and Jettison Piping

R-0000080 A

Table C-4 (continued)

- **APU feed system configuration**
  - Provide APU feed pressure --- (I_Provide APU feed pressure.40)
    - **APU feed DC pump --- (I_APU feed DC pump.55)**
      - APU Feed DC Pump Assembly
  - Receive DC electrical power --- (I_Receive DC electrical power.31)
    - **Power distribution cable harness --- (I_Power distribution cable harness.45)**
      - Left Wing Trailing Edge Cable Harness

R-0000082 A

- **APU feed manifold and piping**
  - Control APU feed --- (I_Control APU feed.49)
    - **APU feed NRV --- (I_APU feed NRV.56)**
      - APU Feed NRV Assembly
    - **APU feed SOV --- (I_APU feed SOV.53)**
      - APU Fuel Shut-off Valve Assembly
    - **Isolation valve --- (I_Isolation valve.57)**
      - Isolation Valve Assembly
  - Transfer fuel --- (I_Transfer fuel.50)
    - **APU feed pipe --- (I_APU feed pipe.54)**
      - APU Feed Piping

R-0000083 A

- **Fuel quantity indicating**
  - Provide probe data --- (I_Provide probe data.35)
    - **Fuel probes --- (I_Fuel probes.58)**
      - Densitometer Assembly
      - Fuel Height Measurement Probe Assembly
      - Velocimeter Assembly
    - **Fuel tank cable harness --- (I_Fuel tank cable harness.1)**
      - Left Wing Leading Edge Cable Harness
      - Left Wing Trailing Edge Cable Harness

R-0000085 A

- **In tank system configuration**
  - Provide probe data --- (I_Provide probe data.35)
    - **Fuel probes --- (I_Fuel probes.58)**
      - Densitometer Assembly
      - Fuel Height Measurement Probe Assembly
      - Velocimeter Assembly
    - **Fuel tank cable harness --- (I_Fuel tank cable harness.1)**
      - Left Wing Leading Edge Cable Harness
      - Left Wing Trailing Edge Cable Harness

R-0000087 A

- **FQIS wiring**
  - Receive control signal --- (I_Receive control signal.33)
    - **Wing leading edge databus --- (I_Wing leading edge databus.4)**
      - Left Wing Leading Edge Databus Wiring

Table C-4 (continued)

  - Receive fuel data --- (I_Receive fuel data.41)
    - **Wing leading edge databus --- (I_Wing leading edge databus.4)**
      - Left Wing Leading Edge Databus Wiring

R-0000088 A

- **Fuel system interactions**
  - Apply pressure refuelling --- (I_Apply pressure refuelling.46)
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly
  - Display refuelling information --- (I_Display refuelling information.53)
    - **Refuel/defuel station --- (I_Refuel/defuel station.70)**
      - Refuel_Defuel Station Assembly

R-0000090 A

- **AC electrical power generation**
  - Receive AC electrical power --- (I_Receive AC electrical power.27)
    - **Power generation cable harness --- (I_Power generation cable harness.43)**
      - Left Wing Power Generation Cable Harness

R-0000098 A

- **Ram air intake**
  - Intake air from warm and cold sources --- (I_Intake air from warm and cold sources.34)
    - **Air filter --- (I_Air filter.26)**
      - Air Filter Assembly
    - **Ram air intake pipe --- (I_Ram air intake pipe.27)**
      - Ram Air Intake Piping

R-0000099 A

- **Engine bleed**
  - Intake air from warm and cold sources --- (I_Intake air from warm and cold sources.34)
    - **Bleed air filter --- (I_Bleed air filter.2)**
      - Bleed Air Filter Assembly
    - **Bleed air pipe --- (I_Bleed air pipe.25)**
      - Engine Bleed Air Piping
    - **Bleed air SOV --- (I_Bleed air SOV.1)**
      - Bleed Air SOV Assembly

R-0000100 A

- **Air supply manifold and piping**
  - Intake air from warm and cold sources --- (I_Intake air from warm and cold sources.34)
    - **Air filter --- (I_Air filter.26)**
      - Air Filter Assembly
    - **Bleed air filter --- (I_Bleed air filter.2)**
      - Bleed Air Filter Assembly
    - **Bleed air SOV --- (I_Bleed air SOV.1)**
      - Bleed Air SOV Assembly

R-0000101 A

- **Temperature control**
  - Generate conditioned air --- (I_Generate conditioned air.23)

Table C-4 (continued)

- **Air conditioning pack --- (I_Air conditioning pack.23)**
  - Air Conditioning Pack Assembly

R-0000102 A

- **Pressure control**
  - Generate conditioned air --- (I_Generate conditioned air.23)
    - **Air conditioning pack --- (I_Air conditioning pack.23)**
      - Air Conditioning Pack Assembly

R-0000103 A

- **Cleanliness control**
  - Generate conditioned air --- (I_Generate conditioned air.23)
    - **Air conditioning pack --- (I_Air conditioning pack.23)**
      - Air Conditioning Pack Assembly

R-0000104 A

- **Icing and fogging prevent**
  - Generate conditioned air --- (I_Generate conditioned air.23)
    - **Air conditioning pack --- (I_Air conditioning pack.23)**
      - Air Conditioning Pack Assembly

R-0000105 A

- **Conditioned air distribution**
  - Distribute conditioned air --- (I_Distribute conditioned air.21)
    - **Air distribution pipe --- (I_Air distribution pipe.24)**
      - Air Conditioning Piping

R-0000106 A

- **Air conditioning manifold and piping**
  - Distribute conditioned air --- (I_Distribute conditioned air.21)
    - **Air distribution pipe --- (I_Air distribution pipe.24)**
      - Air Conditioning Piping
  - Generate conditioned air --- (I_Generate conditioned air.23)
    - **Air conditioning pack --- (I_Air conditioning pack.23)**
      - Air Conditioning Pack Assembly

C.5.2 Tracing from test tasks to requirements

The requirement traceability results shown in table C-4 can be switched to the following manner that would be used in assembly process planning: Test task – Logical component – Physical item – Requirement name – PLM requirement name (see table C-5).

Table C-5 Tracing from test tasks to requirements

- **Air supply pipe airtightness test**
  - **Air filter --- (I_Air filter.26)**
    - Air Filter Assembly
      - **Air supply manifold and piping**
        - R-0000100 A
      - **Ram air intake**
        - R-0000098 A
  - **Bleed air filter --- (I_Bleed air filter.2)**
    - Bleed Air Filter Assembly
      - **Air supply manifold and piping**
        - R-0000100 A
      - **Engine bleed**
        - R-0000099 A
  - **Bleed air pipe --- (I_Bleed air pipe.25)**
    - Engine Bleed Air Piping
      - **Engine bleed**
        - R-0000099 A
  - **Bleed air SOV --- (I_Bleed air SOV.1)**
    - Bleed Air SOV Assembly
      - **Air supply manifold and piping**
        - R-0000100 A
      - **Engine bleed**
        - R-0000099 A
  - **Ram air intake pipe --- (I_Ram air intake pipe.27)**
    - Ram Air Intake Piping
      - **Ram air intake**
        - R-0000098 A
- **APU feed airtightness test**
  - **APU feed NRV --- (I_APU feed NRV.56)**
    - APU Feed NRV Assembly
      - **APU feed manifold and piping**
        - R-0000082 A
  - **APU feed pipe --- (I_APU feed pipe.54)**
    - APU Feed Piping
      - **APU feed manifold and piping**
        - R-0000082 A
  - **APU feed SOV --- (I_APU feed SOV.53)**
    - APU Fuel Shut-off Valve Assembly
      - **APU feed manifold and piping**
        - R-0000082 A
  - **Isolation valve --- (I_Isolation valve.57)**
    - Isolation Valve Assembly
      - **APU feed manifold and piping**
        - R-0000082 A
- **APU feed pump input voltage test**

Table C-5 (continued)

- **APU feed DC pump --- (I_APU feed DC pump.55)**
  - APU Feed DC Pump Assembly
    - **APU feed system configuration**
      - R-0000080 A

Databus wiring continuity test

- **Wing leading edge databus --- (I_Wing leading edge databus.4)**
  - Left Wing Leading Edge Databus Wiring
    - **FQIS wiring**
      - R-0000087 A

Defuel pump input voltage test

- **Aft feed pump --- (I_Aft feed pump.82)**
  - Aft Feed Pump Assembly
    - **Defueling system configuration**
      - R-0000077 A
    - **Feed pumping**
      - R-0000063 A
- **Forward feed pump --- (I_Forward feed pump.46)**
  - Forward Feed Pump Assembly
    - **Defueling system configuration**
      - R-0000077 A
    - **Feed pumping**
      - R-0000063 A
- **Override/Jettison pump --- (I_Override/Jettison pump.47)**
  - Override_Jettison Pump Assembly
    - **Defueling system configuration**
      - R-0000077 A
    - **Feed pumping**
      - R-0000063 A

Electrical wiring continuity test

- **Power distribution cable harness --- (I_Power distribution cable harness.45)**
  - Left Wing Leading Edge Cable Harness
    - **Cross-feed**
      - R-0000064 A
    - **Feed pumping**
      - R-0000063 A
  - Left Wing Trailing Edge Cable Harness
    - **APU feed system configuration**
      - R-0000080 A
    - **Cross-feed**
      - R-0000064 A
    - **Feed pumping**
      - R-0000063 A
- **Power generation cable harness --- (I_Power generation cable harness.43)**
  - Left Wing Power Generation Cable Harness
    - **DC electrical power generation**
      - R-0000091 A
- **Refuel/defuel station --- (I_Refuel/defuel station.70)**

Table C-5 (continued)

- Refuel_Defuel Station Assembly
  - **Refuelling system configuration**
    - R-0000071 A

Feed power-on test

- **Crossfeed valve --- (I_Crossfeed valve.49)**
  - Crossfeed Valve Assembly
    - **Cross-feed**
      - R-0000064 A
- **Engine feed SOV --- (I_Engine feed SOV.51)**
  - Engine Feed SOV Assembly
    - **Cross-feed**
      - R-0000064 A
- **Suction feed valve --- (I_Suction feed valve.50)**
  - Suction Feed Valve Assembly
    - **Cross-feed**
      - R-0000064 A

Feed pump input voltage test

- **Aft feed pump --- (I_Aft feed pump.82)**
  - Aft Feed Pump Assembly
    - **Feed pumping**
      - R-0000063 A
- **Forward feed pump --- (I_Forward feed pump.46)**
  - Forward Feed Pump Assembly
    - **Feed pumping**
      - R-0000063 A
- **Override/Jettison pump --- (I_Override/Jettison pump.47)**
  - Override_Jettison Pump Assembly
    - **Feed pumping**
      - R-0000063 A

Feed system airtightness test

- **Engine feed pipe --- (I_Engine feed pipe.48)**
  - Enginee Feed Piping
    - **Over pressure protection**
      - R-0000065 A
- **Feed NRV --- (I_Feed NRV.52)**
  - Feed NRV Assembly
    - **Over pressure protection**
      - R-0000065 A
- **Other side feed pipe --- (I_Other side feed pipe.83)**
  - Enginee Feed Piping
    - **Over pressure protection**
      - R-0000065 A

Fuel suction/defuel power-on test

- **Defuel SOV --- (I_Defuel SOV.74)**
  - Defuel SOV Assembly
    - **Defueling control**
      - R-0000078 A

Table C-5 (continued)

Defueling system configuration
R-0000077 A
Defuel valve --- (I_Defuel valve.75)
Defuel Valve (Right Side Only) Assembly
Defueling control
R-0000078 A
Defueling system configuration
R-0000077 A
Refuel/defuel station --- (I_Refuel/defuel station.70)
Refuel_Defuel Station Assembly
Defueling control
R-0000078 A
Defueling system configuration
R-0000077 A

Fuel system airtightness test with tank

APU feed pipe --- (I_APU feed pipe.54)
APU Feed Piping
APU feed manifold and piping
R-0000082 A
Check valve --- (I_Check valve.63)
Check Valve Assembly
Vent fuel drain
R-0000069 A
Vent manifold and piping
R-0000070 A
Defuel and jettison pipe --- (I_Defuel and jettison pipe.73)
Defuel and Jettison Piping
Jettison and defuel manifold and piping
R-0000079 A
Engine feed pipe --- (I_Engine feed pipe.48)
Enginee Feed Piping
Feed manifold and piping
R-0000066 A
Float actuated vent valve --- (I_Float actuated vent valve.62)
Float Actuated Vent Valve Assembly
Vent manifold and piping
R-0000070 A
Float drain valve --- (I_Float drain valve.61)
Float Drain Valve Assembly
Vent fuel drain
R-0000069 A
Vent manifold and piping
R-0000070 A
Main tank drain pipe --- (I_Main tank drain pipe.84)
Vent Piping
Vent fuel drain
R-0000069 A

Table C-5 (continued)

- **Vent manifold and piping**
  - R-0000070 A

- **Manifold drain valve --- (I_Manifold drain valve.69)**
  - Manifold Drain Valve
    - **Refuel manifold and piping**
      - R-0000074 A
- **NACA Scoop/Flame arrestor --- (I_NACA Scoop/Flame arrestor.65)**
  - NACA Scoop_Flame Arrestor Assembly
    - **Vent manifold and piping**
      - R-0000070 A
- **Other side feed pipe --- (I_Other side feed pipe.83)**
  - Enginee Feed Piping
    - **Feed manifold and piping**
      - R-0000066 A
- **Refuel pipe --- (I_Refuel pipe.68)**
  - Refuel Piping
    - **Refuel manifold and piping**
      - R-0000074 A
- **Vent pipe --- (I_Vent pipe.60)**
  - Vent Piping
    - **Vent manifold and piping**
      - R-0000070 A

Fuel tank airtightness test

- **Left Centre Tank --- (I_Left Centre Tank.16)**
  - Left Wing Box
    - **Fuel tank installation**
      - R-0000061 A
    - **Fuel tank location**
      - R-0000060 A
    - **Fuel tank test**
      - R-0000062 A
- **Left Main Tank --- (I_Left Main Tank.17)**
  - Left Wing Box
    - **Fuel tank installation**
      - R-0000061 A
    - **Fuel tank location**
      - R-0000060 A
    - **Fuel tank test**
      - R-0000062 A

Jet fuel power-on test

- **Fuel jettison nozzle --- (I_Fuel jettison nozzle.66)**
  - Fuel Jettison Nozzle Assembly
    - **Jettison control**
      - R-0000076 A
- **Jettison valve --- (I_Jettison valve.71)**
  - Jettison Valve Assembly
    - **Jettison control**

Table C-5 (continued)

R-0000076 A

Jettison pump input voltage test

Jettison pump --- (I_Jettison pump.72)

Jettison Pump Assembly

Jettison system configuration

R-0000075 A

Override/Jettison pump --- (I_Override/Jettison pump.47)

Override_Jettison Pump Assembly

Jettison system configuration

R-0000075 A

Refuel system airtightness test

Manifold drain valve --- (I_Manifold drain valve.69)

Manifold Drain Valve

Refuelling system configuration

R-0000071 A

Refuel pipe --- (I_Refuel pipe.68)

Refuel Piping

Refuelling system configuration

R-0000071 A

Refuel/defuel station --- (I_Refuel/defuel station.70)

Refuel_Defuel Station Assembly

Refuelling system configuration

R-0000071 A

Refuel system functional test

Refuel/defuel station --- (I_Refuel/defuel station.70)

Refuel_Defuel Station Assembly

Fuel system interactions

R-0000088 A

Refuelling system configuration

R-0000071 A

Refuel system power-on test

Refuel valve --- (I_Refuel valve.67)

Refuel Valve Assembly

Refuelling system configuration

R-0000071 A

Refuel/defuel station --- (I_Refuel/defuel station.70)

Refuel_Defuel Station Assembly

Fuel system interactions

R-0000088 A

Refuelling control

R-0000072 A

Refuelling system configuration

R-0000071 A

Weight control

R-0000073 A

Surge tank airtightness test

Table C-5 (continued)

- **Left Surge Tank --- (I_Left Surge Tank.18)**
  - Left Wing Box
    - **Surge tank configuration**
      - R-0000067 A

Probe cable wiring continuity test

- **Fuel probes --- (I_Fuel probes.58)**
  - Densitometer Assembly
    - **Fuel quantity indicating**
      - R-0000083 A
    - **In tank system configuration**
      - R-0000085 A
  - Fuel Height Measurement Probe Assembly
    - **Fuel quantity indicating**
      - R-0000083 A
    - **In tank system configuration**
      - R-0000085 A
  - Velocimeter Assembly
    - **Fuel quantity indicating**
      - R-0000083 A
    - **In tank system configuration**
      - R-0000085 A
- **Fuel tank cable harness --- (I_Fuel tank cable harness.1)**
  - Left Wing Leading Edge Cable Harness
    - **Fuel quantity indicating**
      - R-0000083 A
    - **In tank system configuration**
      - R-0000085 A
  - Left Wing Trailing Edge Cable Harness
    - **Fuel quantity indicating**
      - R-0000083 A
    - **In tank system configuration**
      - R-0000085 A

Vent power-on test

- **NACA Scoop/Flame arrestor --- (I_NACA Scoop/Flame arrestor.65)**
  - NACA Scoop_Flame Arrestor Assembly
    - **Tank and system protection**
      - R-0000068 A
- **Re-settable pressure relief valve --- (I_Re-settable pressure relief valve.64)**
  - Re-settable Pressure Relief Valve Assembly
    - **Tank and system protection**
      - R-0000068 A

Vent system airtightness test

- **Check valve --- (I_Check valve.63)**
  - Check Valve Assembly
    - **Surge tank configuration**
      - R-0000067 A
- **Float actuated vent valve --- (I_Float actuated vent valve.62)**

Table C-5 (continued)

Float Actuated Vent Valve Assembly

Surge tank configuration

R-0000067 A

Float drain valve --- (I_Float drain valve.61)

Float Drain Valve Assembly

Surge tank configuration

R-0000067 A

Main tank drain pipe --- (I_Main tank drain pipe.84)

Vent Piping

Surge tank configuration

R-0000067 A

NACA Scoop/Flame arrestor --- (I_NACA Scoop/Flame arrestor.65)

NACA Scoop_Flame Arrestor Assembly

Surge tank configuration

R-0000067 A

Re-settable pressure relief valve --- (I_Re-settable pressure relief valve.64)

Re-settable Pressure Relief Valve Assembly

Surge tank configuration

R-0000067 A

Vent pipe --- (I_Vent pipe.60)

Vent Piping

Surge tank configuration

R-0000067 A

Appendix D Interview

D.1 Brief interviewee profile

A brief profile of five participants is provided in this section in line with Cranfield University research ethical policy.

- Participant A is a researcher in aircraft system design. This participant worked on several design for manufacturing and assembly projects in the aircraft assembly line.
- Participant B is an engineer working in current aircraft industry. This participant is in charge of SE principles application in engineering processes.
- Participant C is an academic teaching aircraft design and maintenance who has been in aircraft industry for more than 50 years. This participant has the knowledge and experience as an assembly operator in shop floor and as a structure designer in aircraft design.
- Participant D is a researcher in aircraft integration field and has more than 20 years working experience in aircraft industry. This participant has the knowledge of aircraft development process in industry, and is working on several aircraft production development projects.
- Participant E is an assembly planner in aircraft industry with 10 years assembly process planning and shop floor experience. This participant is involved in several assembly integration projects including aircraft with distributed and integrated system architectures.

D.2 Interview questions

The aim of this interview is to obtain feedback on the developed methodology from people with knowledge and experience on past aircraft assembly line work.

Part 1: General questions

1. What is your relevant knowledge of aircraft assembly line planning and/or systems engineering?

2. Generally speaking, what kind of aircraft you have experienced? How complicated are these aircraft in your opinion? (You could consider a scale from general aviation aircraft at the lowest level of complexity to a military jet at the highest). Do not provide any business confidential information for this question.

Part 2: Project questions

3. In your opinion, how would you define aircraft complex systems?
4. How do you think system drawings or CAD models currently used in the design process help with understanding the interactions between different systems and sub-systems? Or between components and functions?
5. Can you summarise your understanding of the proposed assembly line planning method based on the presentation you have just seen?
6. What do you think are the benefits of the proposed approach to assembly line planning?
7. Do you think the method could be applied in your industrial context? If not, why not?
8. How feasible do you think assembly sequences generated by this method would be?
9. Are there any aspects of the method that you think are not appropriate?
10. Is there anything you would like to add?