

University of Nottingham
Faculty of Engineering

**Reconfigurable Assembly System Design
Methodology for Aerospace Wing Structures**

Thomas Grant Jefferson, BEng (Hons)

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Abstract

The aerospace industry is facing new challenges to meet burgeoning customer demand. An unprecedented number of orders for commercial aircraft has placed great urgency on aerospace manufacturers to make gains in production efficiency. Wing assembly is one such area where cycle times are in the order of hundreds of hours and commissioning cells can take several years which has led to a significant order backlog. In light of these challenges, new techniques are required to bring about greater agility to respond to market changes. Aerospace manufacturers must seize the opportunity to innovate and readdress approaches to ensure their prosperity. Recent research advocates Reconfigurable Assembly Systems (RAS) as a viable solution. A RAS is designed at the outset to change in structure to modify production capacity and functionality to meet new requirements. Yet, adding reconfigurability further increases design complexity. Despite the increased complexity, few formal methodologies exist to support RAS design for aerostructures.

A novel RAS design methodology is presented to address the design complexity and the specific needs of Airbus. The methodology is a systems design approach consisting of reconfigurability principles, Axiomatic Design and Design Structure Matrices. Customer needs and existing knowledge are used to systematically specify scalable and customisable functionalities from the outset. These requirements and constraints are then translated into physical system designs modelled using CATIA, a 3D modelling software suite.

The design methodology is applied in two case studies for wing assembly to produce full-scale factory designs. The designs are compared with current Airbus baselines in production ramp-up scenarios. The RAS demonstrate capability to change in structure for rapid increase in capacity at comparable cost to fixed systems. Greater capacity and shortened ramp-up time evidently reduces backlog compared to current systems. The first case study focused on technical development of a RAS and found potential ramp-up reduction of 88% and 10% less Capital Expenditure (CapEx) over 10 years. The second case study for a current wing scenario found reductions of 50% to ramp-up and 41% less tooling CapEx compared to a pulse line for a 12-year production cycle. The designs and scenarios were validated in formal Airbus design reviews. The case studies present the first instances of production-scale RAS for aerostructures. The RAS designs are made possible by designing from the outset using a novel design methodology which sets a precedent for the future of aerostructure assembly and opens up new possibilities for future research.

To my Mum and Dad.

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Acronyms

Abbreviation	Expanded Term
AD	Axiomatic Design
AGV	Automatically-Guided Vehicle
AKC	Assembly Key Characteristic
ASD	Assembly System Design
CAD	Computer-Aided Design
CapEx	Capital Expenditure
CFD	Computational Fluid Dynamics
CoS	Condition of Supply
DM	Design Methodology
DML	Dedicated Manufacturing Line
DMU	Digital Mock-Up
DP	Design Parameter
DSM	Design Structure Matrix
FEA	Finite Element Analysis
FMS	Flexible Manufacturing System
FR	Functional Requirement
KC	Key Characteristic
LE	Leading Edge
MAF	Main Assembly Fixture
MDM	Multi-Domain Mapping
MKC	Manufacturing Key Characteristic
NGCW	Next Generation Composite Wing
NRC	Non-Recurring Cost
PDR	Preliminary Design Review
PKC	Performance Key Characteristic
PPS	Product, Process, System
R&D	Research and Development
R&T	Research and Technology
RAS	Reconfigurable Assembly System
RASDM	Reconfigurable Assembly System Design Methodology
RC	Recurring Cost
RMS	Reconfigurable Manufacturing System
SOI	Standard Operating Instructions
TE	Trailing Edge
TRL	Technology Readiness Level

Nomenclature

Abbreviation	Expanded Term	Units
v_c	Cutting speed	Metres/minute
D_{cap}	Cutting diameter at actual depth of cut, a_p	mm
f_z	Feed/tooth	Mm/tooth
z_c	Number of effective teeth	
a_p	Depth of cut	mm
a_e	Working engagement	mm
S_v	Spar cap volume	cm ³
R	Machining time	minutes
v_f	Table feed	mm/minute
Q	Metal removal rate	cm ³ /minute

Chapter 1 Introduction

The following thesis documents new thought on the design of Reconfigurable Assembly Systems (RAS) for primary structures of commercial airliner wings. A novel design methodology is presented and used at Airbus UK to design RAS for two aircraft. The methodology was applied to produce cost-effective system designs that show higher ramp-up and production rates compared to conventional assembly systems. The work contributes a novel design methodology to the field of RAS and establishes the first steps in a new era for aircraft assembly. The following section introduces the current state of practice in aerospace manufacturing at Airbus and future goals. RAS are briefly introduced with insight into characteristics. The opportunity to apply reconfigurability to wing assembly is discussed along with associated problems which form the basis of research questions and objectives.

1.1 Future of Aerospace

The past few years have seen the aerospace industry enter a state of flux. Dynamic demands from airline operators and climate change directives present new challenges for aerospace manufacturers. Long-standing suppliers Airbus and Boeing are facing strong competition from other aircraft manufacturers in emerging countries. Aerospace manufacturing has a key role in solving these new challenges.

The developing economies of India and China are set to more than double the global middle class in the next 20 years. Tourism is anticipated to be a catalyst for economic growth, which will see demand for more aircraft. A total of 31,358 new aircraft are estimated to be delivered between 2014 and 2033 (Airbus S.A.S 2014a). Airbus and Boeing are already struggling with backlogs in excess of 6000 aircraft each (Airbus S.A.S 2015c; The Boeing Company 2014). Tourism is closely linked with the development of aviation in emerging countries and China, Russia and to some extent India, are expected to provide increased amounts of low-cost manufacturing and engineering capacity to the aerospace industry (Bediér et al. 2008). China and Russia also have strategic aims to build aerospace industries comparable to Airbus and Boeing. The Chinese state-owned company Comac has long term goals to break the Airbus-Boeing duopoly on aircraft manufacture (Cliff et al. 2011). It is set to deliver its C919 in late 2018, which is designed to compete with the Airbus A320NEO and Boeing 737MAX. The Russian UAC, which produces the UAC Sukhoi Superjets and Irkut aircraft, received \$28 Billion in state funding to transform into a global competitor to capture market share (Lozano & Eriksson 2015). Canada's Bombardier produce the C-series aircraft to compete with the A320 and 737. It boasts a radical composite structure and wing design coupled with new Pratt and Whitney engines and offers 15% lower operating costs and 25% lower maintenance costs. This aircraft forced the interim retrofit of new efficient engines to the A320 (A320NEO) to maintain order books. By 2033 Bombardier forecast the delivery of 8450 100-149 seat single aisle aircraft (Bombardier Inc. 2014). Brazil's Embraer also have a well-established family of passenger airliners and has launched joint ventures in China and won numerous orders from Chinese airlines (Goldstein 2008). Potentially, five airline manufacturers will be competing for orders of passenger aircraft. Improvements in aerospace manufacturing will be key to ensuring airline manufacturers can offer the shortest lead times at the lowest price.

Burning aviation fuel has a negative impact on the environment, which must be reduced to meet environmental standards. Government directives have been introduced to limit the amount of greenhouse gas production to limit the impact of climate change (Meinshausen et al. 2009). According to (Krein & Williams 2012) by 2050 the European aerospace industry shall reduce CO₂ by 70% and NO_x by 90% along with noise reduction of 65%. The same report targets 4 hours door-to-door for 90% of travellers in Europe by introducing rotorcraft 'vertiports' and advanced air traffic management systems. European aerospace shall also reduce its operating costs and maintain its leading edge in design, manufacturing, R&D and systems integration. As efficient technologies develop, numerous iterations of new efficient aircraft models will be introduced (Isikveren & Schmidt 2014). Aircraft have economic lives of 20-30 years, so new, more efficient models take time to increase fleet

efficiency (Krein & Williams 2012). Airline operators will endeavour to purchase efficient aircraft to minimise operating costs and meet pressing environmental standards. Manufacturers will be expected to respond to changes in technology and demand by delivering new aircraft in compressed timeframes without dramatic increase in production costs.

1.2 Implications for Manufacturing

The increase in aircraft demand is sure to place significant burden on manufacturing and assembly. Aerospace assemblies require complex coordination of people, equipment and information for production; therefore the design of the assembly system will have a large impact on aircraft production cost and time. Assembly is cited to be 15-70% of total manufacturing time and assembly costs are typically 25% to 50% of the total cost of manufacturing (Bi et al. 2007; Lotter & Wiendahl 2009). Naturally, cost affects profit and price. Greater efficiency is needed to remain competitive against new economies which have lower labour costs (Bediér et al. 2008). With future markets set to change, assembly systems need to be able to quickly respond to market change to remain competitive. Typical market changes include demand increase and new, more efficient models. In a globally distributed market, agile production of competitive products has taken priority to seize competitive advantage which is even more crucial in turbulent markets (ElMaraghy 2008, p.6). Aircraft have long lifecycles and so production systems have become outdated. Current assembly systems take too long to change to respond to market opportunities, particularly at Airbus where challenges to market responsiveness are compounded by the current backlog. Assembly methods will have to change to cope with a more dynamic marketplace.

1.3 Current Situation at Airbus UK

Airbus SAS is a global corporation that employs in excess of 73,000 people worldwide. Revenue in 2014 was €42.3bn (Airbus S.A.S 2014b) and 629 aircraft were delivered (Flottau 2015). Airbus has production facilities in France, Germany, Spain and the United Kingdom, as well as subsidiaries in North America, China, India, Japan, the Middle East and Russia. Airbus UK has two sites responsible for production of over 1000 wings per year for civilian and defence aircraft. The Broughton site in Wales is responsible for wing assembly and staffs more than 6000 employees. The Filton site specialises in wing design, aerodynamics research, flight physics and systems and integration. With increasing production rates and target production time reductions, wing assembly is a predominant area of interest to Airbus SAS. The wings are the largest single-piece primary structure assembly. Wing structures must carry the engine, fuel and landing gear, as well as fulfilling requirements for safe flight. Wing assembly is a particularly complex and labour-intensive process for these reasons, and labour and tooling exceeds fuselage assembly when considering both left and right-hand assemblies. Strategic improvement to wing assembly is therefore crucial to meeting future rate requirements and reduction targets.

1.3.1 Wing Assembly Ramp-Up

Wings are currently assembled using large, permanent steel structures to hold the geometry of the components while they are fastened together. A fixture is designed specifically for one aircraft model and a set number of fixtures are built based on projected orders and designed for a fixed maximum capacity. If extra capacity is needed the method of production ramp-up is to build duplicate assembly fixtures. To commission new fixtures takes approximately 24 months. The process requires extensive resources and capital expenditure which limits the number of fixtures that can be built. The dramatic increase in A320 orders has seen the wing assembly system struggle to cope with demand. The factory was originally intended for only eight to ten per month. By 1986, A320 delivery positions were sold out until 1991. The actual first flight was not until 1987. In 1986 Airbus predicted a market for 760 A320s by 2005 (Flight International 1986). By 2005, Airbus had a total of 4701 orders for A320 aircraft and delivered a total of 289 (Airbus S.A.S 2016a). Since introduction, the A320 assembly system has been running at maximum capacity and has failed to keep up with demand. Building extra fixtures has been virtually

continuous and there are now 20 main assembly fixtures producing 46 aircraft a month. The long time to ramp up and limited rate increase has failed to meet demand and at the end of 2014 the backlog of orders for A320 was 6193 (Airbus S.A.S 2016a). Some orders have been cancelled or reduced and delayed deliveries have been penalised. Existing orders that go undelivered present inaccessible cash flow. What's more Airbus forecast demand for over 30,000 passenger and freighter aircraft by 2033, of which single-aisle passenger aircraft represents the largest segment at 22,071 (including backlog). The current wing assembly systems are not designed to readily increase capacity. To maintain advantage in the global marketplace, the future systems need to be have greater ramp up capability. Key lessons can be learnt from the current production approach and new methods can be devised to design more responsive assembly systems with greater ramp-up efficiency.

1.3.2 Modifying the Assembly System for Change

One problem associated with ramp up is that the current assembly systems are difficult to change. Design of the A320 assembly system began in the early 1980s and is still in production. Aside from duplicating fixtures, the cycle time of the fixture could be improved with modifications or new manufacturing technologies. The problem is that implementing these changes involves extensive modification to the fixtures because the fixture design is inflexible. Changes to a small section require changes throughout the fixture. This problem is also evident with implementing changes to aircraft models such as the New Engine Option (NEO). Modifications involve a high cost because of the amount of redesign work and implementation which also adds the long lead time which causes delays. Increasing flexibility in the assembly system design (ASD) should allow the systems to evolve with new technologies and replace aging subsystems.

1.3.3 Airbus Targets and Aspirations

For Airbus UK to remain competitive (globally and within Airbus SAS) future wing programs and assembly systems must improve efficiency. This will be an ongoing and iterative process involving future aircraft programs and step changes in current manufacturing. Airbus UK have stated ongoing reduction targets to improve the capacity and flexibility of equipment and reduce non-recurring costs and time-to-market (Millar & Kihlman 2009; Airbus UK 2007). The current backlog is considered as part of the global forecast so specific targets are unspecified. Though, the A320 backlog is a top priority with the introduction of a new production line to increase production rate. Airbus targets for future assembly tooling include a reduction of 30% in capital expenditure on tooling, 50% increase in production capacity, 50% reduction in ramp-up or greater and 40% reduction in costs (Millar & Kihlman 2009; Airbus UK 2007; Airbus UK 2012). Targets are borne of discussions with Airbus engineers and the Flightpath 2050 roadmap (Krein & Williams 2012).

1.4 Reconfigurable Assembly Systems

Yoram Koren *et al* (Koren *et al.* 1999) proposed Reconfigurable Manufacturing Systems (RMS) as a new type of manufacturing system designed to respond quickly and profitably to market changes. Reconfigurable Assembly Systems (RAS) are a subset of this paradigm and are designed from the outset for cost-effective change in capacity and functionality to respond to market changes. RAS are designed to change optimal parts of the physical structure by adding or removing modular elements or modifying customisable elements. RAS combine the high throughput of a Dedicated Manufacturing Line (DML) and the flexibility of a Flexible Manufacturing System (FMS) but are designed in such a way to change in structure quickly and efficiently without excessive cost (Koren & Shpitalni 2010). An assembly system is likely to be reconfigurable when it possesses six characteristics. *Customisation*, *Scalability* and *Convertibility* are essential characteristics for RMS (Koren 2006). Descriptions of essential characteristics for RAS are presented in Table 1 with aerospace examples. *Modularity*, *Integrability* and *Diagnosability* enable and support the efficiency of RMS, described in Table 2. To realise a cost-effective RAS for aerospace essential characteristics are integrated as a systems approach to design that allows reconfiguration of the entire system, hardware and software.

Table 1. Essential Characteristics for RAS

Characteristic	Description
Customisation (flexibility limited to part family)	Customisation refers to designing a system for assembling an entire product family. So a system or machine flexibility is limited to a single product family, thereby obtaining customised flexibility. Design a system for wing family, customising for differences such as size and shape.
Convertibility (design for functionality changes)	The ability to easily transform the functionality of existing systems and machines to suit new production requirements. Convertibility means that it is possible to switch quickly from the assembly of a certain product to the assembly of a different product in the product family. Convertibility involves adding or changing functionality. For example converting production from wing assembly to fuselage assembly.
Scalability (design for capacity changes)	The ability to easily modify production capacity by adding or subtracting manufacturing resources (e.g. machines) and/or changing components of the system. Scalability means the ability to change system throughput in a relatively short time to match demand. Thus, the system is designed to vary production capacity when demand changes.

Source: Adapted from Koren & Shpitalni (2010)

Table 2. Enabling Characteristics of RAS

Characteristic	Description
Modularity (components are modular)	The compartmentalisation of operational functions into units that can be manipulated between alternate production schemes for optimal arrangement. Includes system, hardware and software. A facilitator of other characteristics.
Integrability (interfaces for rapid integration)	The ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that facilitate integration and communication. Integration applies throughout the entire enterprise. For example, the product design should easily integrate with fixture design, as well as hardware integration.
Diagnosability (design for easy diagnostics)	The ability to automatically read the current state of a system to detect and diagnose the root causes of output product defects, and quickly correct operational defects. This would apply to detection of machine failure or unacceptable quality.

Source: Adapted from Koren & Shpitalni (2010)

1.4.1 RAS in Other Industries

RAS have been used in other areas, particularly automotive (Colledani et al. 2016). RAS are more prominent in the high-volume sectors of the automotive industry where there are multiple models. RAS have perhaps not been used in aerospace because of long lifecycles of aircraft and reliance on current systems. A conservative approach in regard to safety has meant manufacture and assembly is less understood. Also, the RAS technologies have not been able to cope with the tolerances and size of the components. Future rates and model variety are now more critical and so RAS is gaining interest (Millar & Kihlman 2009).

1.5 Opportunity

Airbus S.A.S is facing a marked increase in future air travel and strong competition from rivals with lower operating costs. The aerospace industry has reached a juncture where continuing with conventional assembly methods risks losing technical edge in production. Airbus' current circumstance presents an opportunity for innovation to readdress approaches to aerospace manufacture. Continued success should endeavour to challenge thinking to stay ahead of the competition. Wing assembly is set to play a crucial role in delivering competitive aircraft to market in the shortest possible time. Airbus UK are to

lead development of all manner of wing programmes and will build on industry-leading expertise. Various aircraft are in conceptual development including the one presented in Figure 1 along with supporting technology development. Figure 1 also presents an Airbus UK research framework for Next Generation Composite Wings (NGCW) which will include major studies into high volume, low-cost assembly. RAS are expected to be the dominant approach in wing assembly since they offer cost-effective change in capacity and functionality.



Figure 1. Airbus Concept Aircraft (left) and Next Generation Composite Wing research framework (right) (The Engineer 2014; Airbus UK 2012)

1.5.1 Application to Wing Assembly

A RAS designed for changes in capacity and functionality could provide the faster response needed to cope with market demand and deal with model changes. Cost-effective reconfigurability at the system level is currently non-existent in wing assembly. The lack of ramp up capability in current assembly systems is limiting production and competition from emerging economies are gaining advantage by offering similar delivery times but with much lower manufacturing costs. As of yet, only the changing structures of RAS addresses the ramp-up challenge (Bi et al. 2008). A system layout designed with greater independence should allow structural changes to be made to decrease cycle time of assembly processes and thus increase production rate with greater ease.

1.5.2 RAS for Future Aircraft Assembly

The design of new aircraft is underway at Airbus, so there is an opportunity to revise the ASD. The problems associated with ramp up can be reduced or alleviated with the launch of new aircraft. Airbus NGCW will look at different technologies across design, manufacture, assembly and equipping to feed into the next generation single-aisle aircraft, primarily to reduce mass, production costs and lead times. These technologies will be integrated into manufacturing and assembly facilities. This presents an opportunity to design the system to ramp up easily. Production targets for the aircraft are not fixed, so the factory requires flexibility and the design needs a level of independence to change for technologies and new models. The aircraft design has not been frozen so assembly has a chance to influence some design decisions concurrently. RAS is a prime solution to address the needs for flexibility in wing assembly.

Advancements in technology mean RAS is feasible for aerospace. The cost of automation is making reconfigurability more affordable for aircraft assembly (Kihlman et al. 2004; Olsson et al. 2010). Metrology systems have progressed in accuracy and usability, and can now be used to determine the position of parts within aerospace tolerances (Martin et al. 2011; Muelaner et al. 2013). Tangent developments in integrating metrology systems with robotics means robots can now be used for aerospace assembly applications (Gray et al. 2013; Saund & DeVlieg 2013). Robots have also been developed with a mobile capability and multi-functionality so that they may move around the factory to carry out various tasks (Gray et al. 2013; Adams 2014). Flexible fixtures have also been used successfully to assemble aircraft structures (Millar & Kihlman 2009; Kihlman & Engström 2010). In principle, an assembly system using these technologies could provide the characteristics of scalability and customisation necessary for a RAS for wing assembly.

1.6 Lack of RAS Design Methodologies

These developments mean assembly technologies can now be characterised as scalable and customisable and so demonstrate the characteristics of a RAS *if* they are supplying capacity and functionality changes. Given these developments, a RAS can be designed from a practical standpoint and deploy these technologies in specific areas that will allow the system to ramp up. Despite opportunity for RAS in aerospace due to technological advances, there are few suitable methods to systematically design a working RAS suitable for aerostructure assembly.

There is a general lack of RAS design methodologies cited in academia (Bi et al. 2008; Koren & Shpitalni 2010; Rösiö & Säfsen 2013). The difficulty of design is attributed to the large commitment of manpower and skill for the specification and integration of complex manufacturing elements (Abdi & Labib 2003). Existing design methodologies focus on variety (Al-Zaher et al. 2013) or product platform formation (Kashkoush & ElMaraghy 2014) where mass customisation is the main goal. These methodologies generally consider automotive products where RAS is more prominent because of greater commonality and standardised tooling. Automotive assembly systems design places more emphasis on product variety (Hu et al. 2011) where the industry is driven by producing many variants in the shortest time possible and introducing new models to market quickly (Michalos et al. 2010). This renders the existing methodologies unexplored for design for capacity change. Very few examples demonstrate systems designed for ramp-up and capacity change for component scales similar to aerospace. Aerospace primarily requires more capacity flexibility over a longer period of time to go from low demand to high demand.

1.7 Research Aim

The aim of the work is to explore RAS design for wing structure assembly. This particular research focuses on the design of RAS and how to design RAS for the particular challenges of aerospace assembly. The work will contribute to adopting RAS design practices in the future and aid the Airbus transition to productionised RAS. Practical RAS designs will be developed using existing technologies as part of Airbus future aircraft programs. The study will show the benefits and drawbacks of a RAS when compared to conventional assembly systems. The study will compare both approaches for potential investment. The RAS design will also support the early stages of supply chain set up and potential technology acquisition. Direction is also given to future research.

This research contributes to an overall goal of a full-scale production RAS for future wing structures. The work is a small part of ongoing development to progress Airbus to a functioning RAS for wing assembly. What's more, a RAS for wing assembly forms only a fraction of the technical challenges present in an aircraft program. Aircraft programs have lifecycles between 5 and 20 years because of the development effort required. There is significant input and cooperation required from design, manufacturing, certification, aviation authorities, procurement, operations and business and marketing. The work will go through numerous iterations beyond this thesis and ultimately converge on production solutions in time for design freeze and aircraft launch.

1.8 Motivation

Careful deliberation and discussion amongst senior Airbus Manufacturing Research and Technology (R&T) personnel and academics elicited eminent challenges in regard to RAS design. A key point of concern is how to address issues in designing a RAS suited to aerospace assembly and Airbus. The research should enable straightforward transition from current approach to reconfigurability and complement existing abilities and practices. The issues raised guide the research question formulation and are defined as follows:

- a) **Capturing and applying data** – Aerospace design is an iterative process and has to consider multiple, and often conflicting data sources which all exert influence on the ASD. Much of the design data in aerospace is tacit and often

incomplete in the early phases of the lifecycle. Consideration should be given to compiling all the data from numerous sources and feeding the relevant data into design.

- b) **Design from the outset for reconfigurability** – A RAS must be designed from the outset to embody the scalability and customisation characteristics. To this end, scalability and customisation must be specified somewhere in the design process.
- c) **Translate requirements into physical solutions** – RAS are naturally more complex than DMLs because of the capability to change in structure. This makes the design process inherently more complex where scalable and customisable requirements have been specified in particular areas and must be then associated with a physical system capable of reconfiguring.
- d) **Modelling a RAS** – Using RAS over DML adds design and operational complexity. A RAS should be represented in such a way that the impact of reconfigurations can be assessed prior to implementation.
- e) **Investment for Airbus** – This is Airbus' first major study into production-scale RAS. Airbus regularly reviews projects for further research and investment. Capital Expenditure and factory capacity are prominent factors for assembly system investment. To assist decision making a RAS should be compared with an equivalent DML for advantages and drawbacks.

1.9 Research Questions

The research questions will centre and guide the research towards addressing the challenges of RAS design and contributing to the project aims. From the problems discussed in motivation, one can postulate that: In order to design a RAS for wing structure assembly, some form of design methodology (DM) needs to be employed. From this an overarching research question can be defined as a major line of inquiry:

Research Question: *How can a reconfigurable assembly system be designed for cost-effective wing structure assembly?*

The research question is formulated into a series of questions to guide specific areas of investigation. Each question is written specifically to address the challenges and achieve the project aims. The research questions are stated here formally and used to set objectives. Each objective will be pursued in the course of the thesis to answer each research question. The remainder of this section provides a description with each stated question.

Question 1: *How can existing knowledge and product requirements be translated into assembly system requirements?*

The ASD is influenced by multiple data sources with varying relevance. The challenge is to capture and review data to create a relevant set of RAS requirements made from a combination of existing work and customer requirements. The design and manufacturing of an aircraft is an iterative process and so many solutions are still in development during ASD. RAS design should use solutions and knowledge gathered from R&D work and lessons learnt to influence the system design. Much of aerospace knowledge is tacit, Airbus rely on the abilities of engineers to deliver designs. The RAS should maximise use of this design knowledge. Airbus have stringent and complex procedures for design so any methods should be suitable for designing a RAS in this environment.

Question 2: *How can scalability and customisation be specified from the design outset?*

Koren *et al* (1999; 2010) state that: 'a RAS is designed at the outset for rapid change in structure to provide exactly the capacity and functionality needed when it is needed.' The assembly system should possess scalable and customisable characteristics in order to reconfigure. These should be specified somewhere in the RAS requirements so that they

may be satisfied by physical solutions. The requirements should be congruent to aerospace customer requirements and Airbus practices.

Question 3: *How can RAS requirements be translated into working assembly system designs?*

To translate neutral requirements into physical designs requires careful designer input which must draw on existing work and the customer requirements as well as experience. The designer must construct a practical system architecture which can physically change. The technical development and 3D design of the system must directly link to requirements to ensure reconfigurability characteristics are embodied in the physical design.

Question 4: *What methods can be used to model reconfigurable implementations?*

A reconfiguration involves adding or modifying parts of the system. This means changes to equipment, processes, scheduling, logistics, labour which all have an associated cost and time. The system needs to be modelled and analysed in some way to evaluate these changes for feasibility prior to execution.

Question 5: *How does an Airbus RAS compare with a conventional assembly system for investment?*

A RAS must show clear demonstrable benefits over a conventional assembly system to be a valid investment. A RAS must also be technically feasible and cost-effective. Equally, verification of the methodology by producing a RAS design that has investment potential and comparable technical feasibility will be vital in an Airbus transition to reconfigurable methods. Comparisons with a conventional system will also inform Airbus in understanding risks and planning future work.

1.10 Overview of Study

This section details how the research will be conducted. The research is situated in three fields of study: Engineering Design, Reconfigurable Assembly Systems and Aerospace Assembly. To answer the research questions a line of inquiry will be followed by satisfying a series of objectives, derived from the research questions and Airbus. The work will begin with an industrial review to establish Airbus requirements for a DM. This will guide a literature search for appropriate methods, frameworks, tools and the like. Design and testing of a DM will follow and then be applied to design RAS for wing structure assembly projects.

1.10.1 Research Objectives

The following research objectives are pursued in order to structure the investigation and answer the research questions. Each objective is briefly described.

Objective 1: *Examine current assembly systems and identify limitations*

The current Airbus assembly systems are reviewed to identify any implications for RAS design and implementation. The RAS must operate according to Airbus aerostructure assembly objectives and so a review is necessary to determine feasibility of implementing an aerostructure RAS. The limitations of the current assembly systems are outlined in detail so that they may be addressed with the application of a RASDM. The state-of-the-art of assembly systems will set requirements of the DM functions to produce a real-world assembly system. The current assembly systems and ramp up capabilities will be used as a baseline for comparison with a RAS.

Objective 2: *Examine current design practices and identify data types*

The DM will be applied to industrial Airbus projects for validation of the methodology and so must function with Airbus processes. Airbus design practices are reviewed to develop requirements for a compatible RASDM. This includes identifying what data sources are used and the type of design information needed for assembly.

Objective 3: Determine feasibility of RAS application for wing assembly

Airbus intend to implement RAS so it must use real-world technologies. A RAS by definition must employ scalable and customisable equipment and processes. Airbus assembly is typically conservative and prefer to use certified equipment and processes already in use on aircraft to reduce certification costs. A review of reconfigurable assembly technologies will be conducted to understand which ones are suited to aerospace. This will highlight the available technologies and technical feasibility of a RAS at Airbus.

Objective 4: Specify the requirements for an Airbus RAS design method

A set of requirements is created from objectives 1-3 to select a suitable methodology that can deliver a RAS for Airbus aerostructure assembly. The requirements guide the literature search and define the DM functions. Requirements of a methodology are elicited from current assembly systems and design practices to ensure the DM is fit for a RAS at Airbus and resolves the current assembly system limitations.

Objective 5: Identify and compare existing methodologies suitable for RAS design

Find a suitable methodology that satisfies Airbus requirements for a RASDM. Conduct a systematic literature review by comparing existing methodologies with the DM requirements. Examine existing methods suitable for RAS design based on baseline findings and requirements of methodology. Review published literature in RAS design. Search for complete methodologies with practical application as well as frameworks and principles. Using the requirements outlined by objective 4 will highlight the methods most applicable to Airbus RAS design.

Objective 6: Adapt or develop a design methodology for Airbus RAS design

Create or adapt a DM which satisfies Airbus DM requirements. This may be a combination of methods or development of a new method. The outcome of objective 5 will reveal any knowledge gaps where requirements are not satisfied or where multiple methods need to be integrated into a methodology.

Objective 7: Validate the design methodology by designing a RAS using real-world Airbus wing assembly case study applications

The methodology will be applied to industrial case studies for validation. Case studies will demonstrate characteristics for scalability and customisation. Ramp up capability, production rate and cost will be quantified and compared to a conventional baseline established in objective 1.

1.10.2 Thesis Structure

The thesis consists of eight further chapters. The industrial context, field of research, problems and aims of the project have been described along with the research questions and objectives in chapter one. Future demand for aircraft means production systems have to respond to changes in demand to remain competitive. RAS have this capability when designed appropriately but currently there is no systematic way evident for aircraft assembly. Chapter two benchmarks industrial practices to elicit the requirements of

RASDM. The current assembly systems are not capable of efficient ramp-up. RAS are a potential solution for aerospace, given deliberate design. RAS design is a complex process and Aircraft design at Airbus has specific challenges. Chapter three is a literature search for appropriate RAS design methods for application to wing structure assembly. The literature is critiqued for satisfaction of the DM requirements outlined in Chapter two. Where the literature does not satisfy the industrial requirements is indicative of knowledge gaps. To satisfy the DM requirements a method or methods will have to be modified and tested. The procedure devised for carrying out the development and testing of a DM is outlined in chapter four; the research methodology. The fifth chapter presents the RASDM and the supporting rationale for its conception. The two following chapters present case study applications of the RASDM applied to industrial projects for wing structure assembly using Airbus data. The first case study deals with future aircraft and validates the RASDM for its role as a future RAS for wing assembly. The second case study deals with the current A320 aircraft which requires greater ramp up capability because of high backlog. Investment analysis is conducted with a comparison to a non-reconfigurable baseline. A short discussion of findings is presented in each case study chapter. A thorough discussion of the case study results is presented in chapter eight. The conclusions drawn from chapter eight are presented in detail in chapter nine along with retrospective critique of the investigation and suggestions for further work.

1.11 Significance of Study

The research presented presents a valuable step towards RAS for wing assembly. There is an obvious commercial interest to Airbus UK and to the aerospace industry in general which is in need of new manufacturing solutions to cope with unstable markets and fluctuations in demand. The work provides a foundation to implement a RAS for primary wing structures. The DM derived from the research can be used elsewhere for development and contribute towards the broader field of RMS. The investigation extends the knowledge of RAS design by conceiving a novel methodology which deals with designing from the outset for scalability and customisation, focusing more on detailed design of physically reconfigurable architecture for capacity increase. The field of RAS design is advanced and now includes a practical DM for physical implementation. The RASDM yields practical system designs to contribute to solving ramp up and capacity increase to current industry problems. Significant advances are made in aerospace assembly by designing a system able to increase capacity with duplication of tooling. An increase in system independence made possible by the DM means systems can more easily be upgraded for new technologies or new model variants. The Airbus transition to RAS is achieved by developing a methodology that functions with Airbus data and corporate structure. Long term benefits will see improvement to productivity and an increase in revenue. Review of current practice and its input to the DM shall improve Airbus design and shorten the design lifecycle. Positive improvement is also found in having reconfigurable assembly design input in the early phase of aircraft programs to make components more suitable for assembly; further reducing cost and increasing throughput.

Chapter 2 Industrial Review

This chapter contextualises the situation so that the research is useful and meaningful to Airbus. It highlights the specific limitations of the current assembly systems and design practices and contributes to a baseline for future comparison. The data types for design are also examined to develop a compatible DM. The products to be reconfigured are introduced. The potential of RAS to address these limitations is critiqued as is the technical feasibility of implementing a RAS.

The implications of a RAS for Airbus wing assembly are used to formulate the requirements for a DM. This is to create a DM which is suitable for use at Airbus and addresses the challenges. Objectives 1-4 are pursued in turn. Objectives 1 and 2 draw on a range of sources for information. Objective 3 seeks to critically examine the findings for implications for RAS design and implementation at Airbus. From this, a set of DM requirements are specified for objective 4. Limitations are determined and used to specify meaningful requirements for finding solutions. Requirements derived from analysis of Airbus-specific practices and needs are more meaningful and direct the research to appropriate solutions. As further credibility, the set of requirements are approved by Airbus. Figure 2 illustrates the chapter structure and how the main aspects of the industrial review inform RASDM requirements.

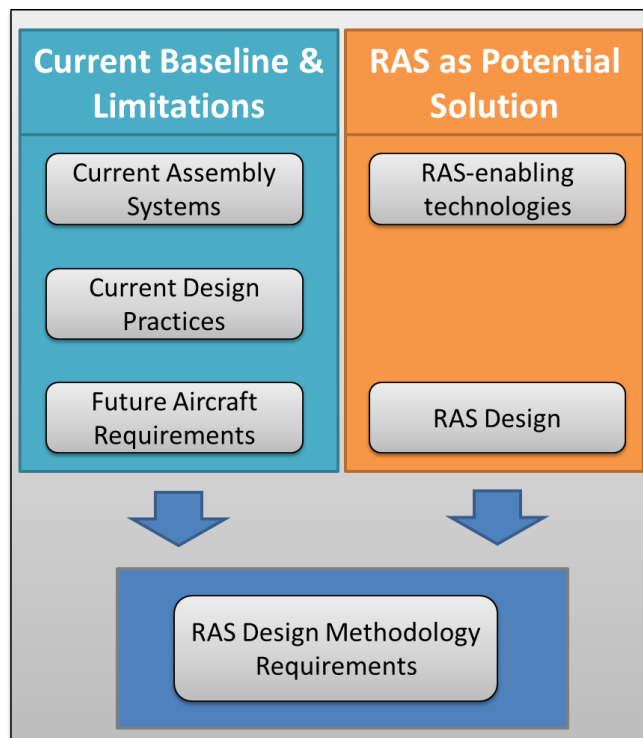


Figure 2. Chapter two structure

The aim of the industry review is to investigate the design implications of RAS for future Airbus wing production. A set of requirements for a DM is outlined to meet the specific needs of Airbus design and RAS design. The current assembly systems are reviewed to understand the implications for transition to a RAS. Equally, Airbus design practices are scrutinised for implications of designing a RAS. The future wing design is discussed for production using a RAS. The limitations of current assembly systems and design practices for future production at Airbus Operations UK are defined. Current assembly systems and design practices form the baseline for comparison with research and characterise the problem to develop meaningful requirements. The feasibility of a RAS solution for these limitations is addressed. The design issues are also considered for a RAS for wing structures and constructed into requirements for a RASDM.

2.1 Current State of Assembly Systems

Aerospace assembly systems generally use a lot of manual operations. This section focuses primarily on wing assembly which is where the research will be applied. The current state of assembly systems is split into the product to be assembled; the wing, the assembly processes and the equipment used during assembly to highlight the technical challenges in ramp-up of production and the operational complexity of design. Making this system reconfigurable over static may potentially add additional complexity to an already complex system. The DM should minimise complexity. Critique is provided on how this influences a RAS including what particular aspects a RAS has to conform to at Airbus. The fiscal impact of the ramp up limitations is shown using historical data. The importance of assembly in aerospace and typical costs is explained. Also described are primary structures and main challenges for future production which are ramp-up and model change due to dependence. Finally, implications for transition to reconfigurable assembly are stated to be used for formulation of the DM requirements. The information presented here is borne out of internal documents, industrial projects and observations at Airbus, ElectroImpact and the Manufacturing Technology Centre (MTC).

2.1.1 Wing Primary Structures

This section describes the primary structures components and assembly process to produce a commercial aircraft wing. The assembly system produces the aircraft wing. The aircraft reviewed are A320 and A350 which have experienced the strongest ramp up issues. A380 is not included in the review because volumes are lower and future projections expect the biggest impact to be single-aisle aircraft. A350 is included because it is the most advanced production line in operation at Airbus but has had issues with ramp up and is not capable of increasing capacity.

2.1.1.1 Primary Structures

Aircraft primary structures sustain the major loads for take-off, flight and landing. Wing primary structures generally consist of front and rear spars, wing box ribs, pylon fittings, landing gear structure and the upper and lower covers. Figure 3 presents a sketch of the primary structures of a typical commercial wing. Figure 4 presents an exploded view of a 3D A320 CAD model. The assembled primary structure is presented in Figure 5.

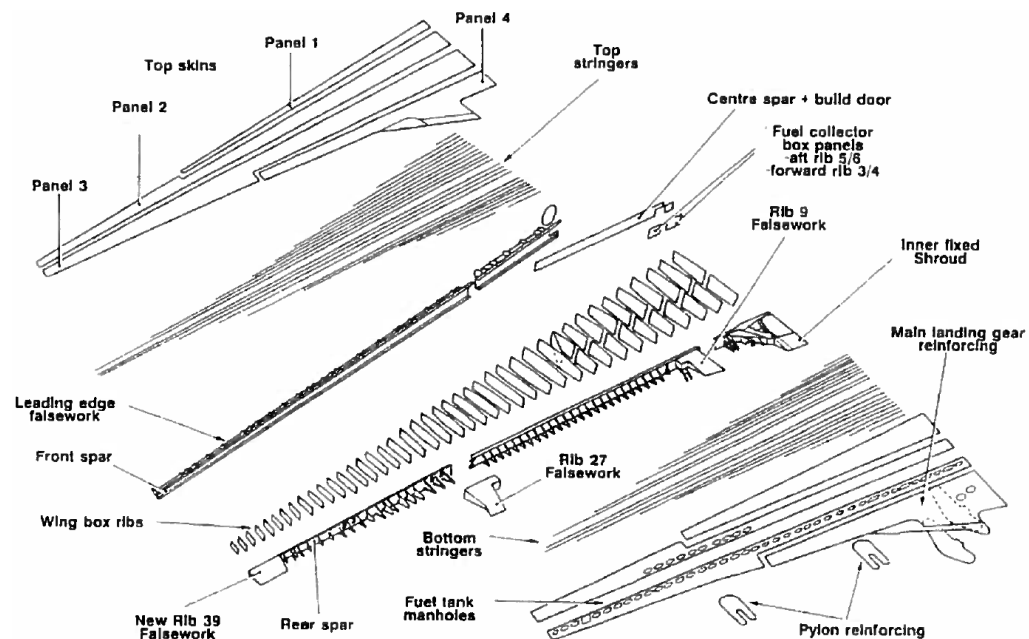


Figure 3. Primary structures of a typical wing (Airbus UK 2009a)

Commercial wing primary structures in particular are subject to high loads from landing impacts, engine thrust and mounting the engines themselves as well as aerodynamic forces. The structure must absorb these loads through the life of the aircraft without succumbing to structural failure. The structural integrity of these components is paramount to safe air travel and so the design, manufacture and assembly processes are carefully controlled by Airbus protocol and certified by external bodies.

The wing assembly maintains the necessary geometry to safely function as an aerofoil and primary structure of the aircraft. The assembly is made up of a number of Key Characteristics (KCs) specified in design GD&T which relate to Performance, Assembly and Manufacturing. KCs do not specify how the wing should be made but simply what requirements the wing must conform to. PKCs are tolerance requirements relating to the performance of the aircraft, typically aerodynamic or flight manoeuvres. AKCs are tolerances of the assemblies and subassemblies such as the trailing edge spar and hinge ribs. MKCs apply to manufacturing processes such as machining or forming.

The wingbox is comprised of the spars and ribs and provides some of the structure to support the aerodynamic surfaces in flight. The upper and lower cover are fastened to the wing box and add to the structural integrity. Unassembled, the components are extremely compliant and do not remain rigid under their own load. Deflections of several centimetres can be seen on unfixtured spars and the larger ribs while covers see deflections of up to a metre. Components have to be manipulated into place using external forces such as clamps to manoeuvre the components into the fixture.

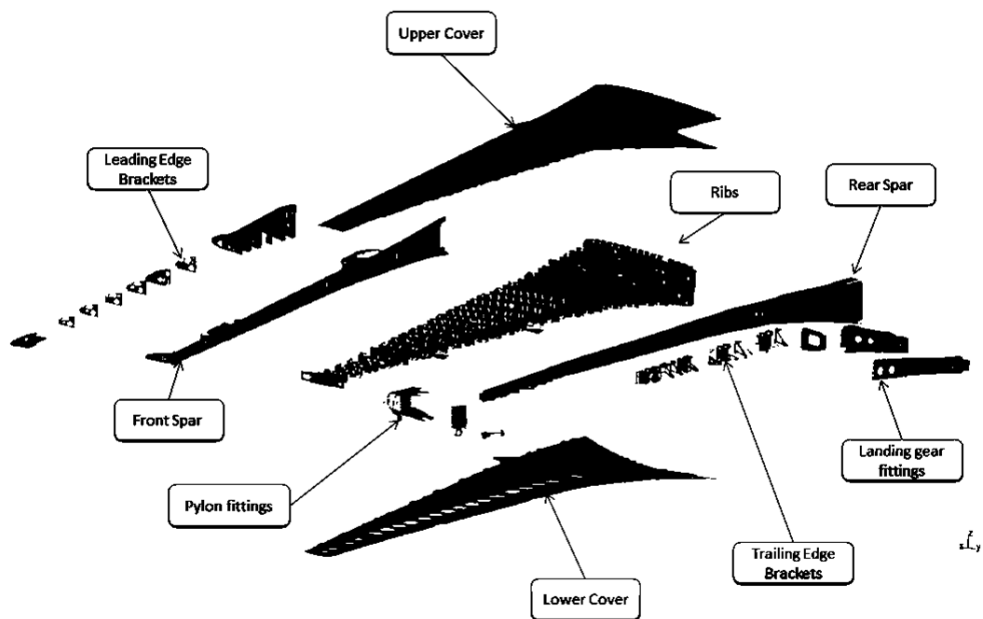


Figure 4. Exploded view of A320 wing primary structures

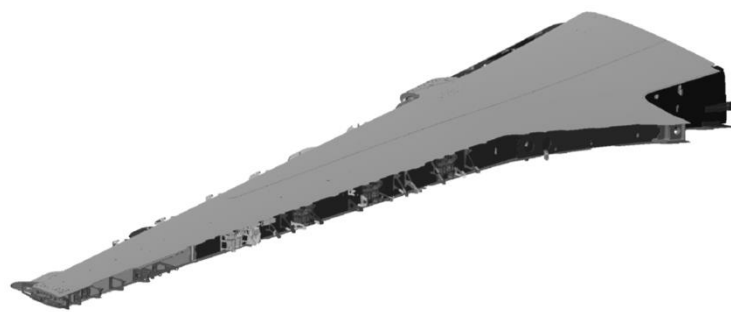


Figure 5. CAD model image of an assembled A320 wing structure, approximately 15m in length from root to tip

2.1.2 Assembly Process

Due to the importance of structural integrity of the structure for safety, the wing structure assembly process is subject to strict control to ensure the components are assembled within the tolerances stipulated by design (Campbell 2006). The tolerances are tight due to structural performance and aerodynamic performance. The spars and covers are approximately 15m in length and assembled to PKC tolerances of $\pm 0.1\text{mm}$ in some areas. The structures are compliant and exhibit large deflections during handling which adds to the difficulty of assembly. Structures are located and drilled and fastened in-situ to avoid misalignment. The basic assembly sequence for wing structures is depicted in Figure 6.

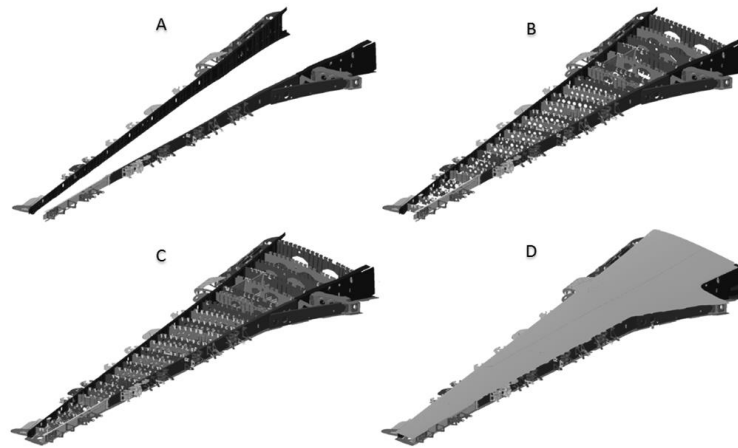


Figure 6. Spars (A) are constrained by ribs (B) which is followed by fastening lower (C) and upper (D) covers

A typical assembly process is as follows: Undrilled spar subassemblies are loaded into a fixture and their geometries are constrained using mechanical tooling. Ribs are then positioned inside the spars and located with edge gauges. Drilling templates are used to drill the rib to spar interfaces. The ribs are then removed and deburred and sealant is applied if the wing is used to store aviation fuel. The ribs are then relocated in the spars and fastened. The upper and lower cover are then positioned to the wingbox and a series of holes are drilled and inserted with temporary fasteners. This is to hold the wing cover and close gaps to the ribs during drilling of the cover to rib feet interfaces. Drilling templates are used again and the covers are removed for cleaning and sealant application before being relocated and fastened. The wing structure is now complete and can be removed and shipped for final assembly to the fuselage.

A typical commercial aircraft can have between 1,500,000–3,000,000 fasteners which must be drilled and installed with a fastener. The wings are assembled either horizontally or vertically and are assembled in either a static fixture or on an assembly line. Most configurations have been used successfully. Vertical-static is the most common method because the tolerances can be maintained on the compliant parts. The components are drilled in-situ because of the compliance in the components, handling challenges and inaccuracies in the fixture. Assemblies often require disassembly after drilling to de-burr the components and apply sealant to meet stringent safety requirements. Metallic liquid shims are used where there are gaps and this is also strictly controlled.

Commercial aerostructures don't usually arrive pre-drilled because of the high risk of misalignment. This is attributed to a number of factors including temperature change in the factory, machining capability and the interference fits of the fasteners which are tight because of the structural requirements. Drilling is done manually on the A320 because it is an older aircraft and automation was unfeasible. The A350 has automated drilling of the upper and lower covers where there is clear access but requires some manual setup procedures. The ribs to spars are drilled manually because of automation inaccessibility. Access is often a deciding factor in drilling because automation cannot access areas of the wing. Manual drilling processes have been used extensively in aerospace since aircraft became prominent and are well understood and therefore easier to certify. Automation is more difficult to certify because there needs to be absolute confidence in the control of the

process. Because of the high manual involvement, ergonomics become a critical factor in ASD. The large number of holes and manual drilling make wing assembly a labour-intensive process. There are over 2000 parts on the A320 wing excluding fasteners which all have unique part number identifiers for certification traceability. The wing assembly process has high operational complexity because of airworthiness law. The assembly process management uses a 'build network' which is a spreadsheet database of all the assembly operations and associated information. At Airbus UK this is handled in Microsoft Excel or Microsoft Project and shows labour content, cycle time, process order, part numbers etc. The manual operations are controlled by Standard Operating Instructions (SOIs). SOIs govern the practical procedures carried out by the operators for assembly. They are usually issued as a paper documents to the assembly fixture. They contain detailed assembly instructions and contain part numbers, tool numbers, other document references, torque values and annotated images. The documents are reissued if changes are made and a detailed issue history is also included along with the engineer's name.

The assembly process is subject to strict control to ensure the safe operation of the aircraft. The assembly process is time consuming and labour-intensive and in some cases constrained to dated production methods because of certification cost. The processes are strongly dependent on one another and a minor change to one process affects many connected processes. This limits the options for improving cycle times because the economic benefit is exceeded by the cost.

2.1.3 Assembly Fixtures

The wing assembly process takes place in an assembly fixture which positions the components so they can be assembled. Fixtures are large in structure to accommodate the wing shape and structurally stable to hold tolerances and forces of wing assembly which is detailed during certification. Typically wings are assembled vertically or horizontally in a static fixture or on a pulse-type assembly line where a subassembly is completed and transferred in stages to independent cells. Fixtures can also be automated or manual or a combination of both. Assembly fixtures are discussed for two Airbus aircraft. A320 fixtures represent the highest production rate in aerospace and A350 represents the current-state-of-the art for Airbus wing assembly.

2.1.3.1 A320 Fixtures

A320 assembly is a vertical build which takes place in steel fixtures designed around the wing geometry presented in Figure 8. Fixtures are approximately 18m x 8m x 8m to accommodate port and starboard wing builds. Figure 7 is an image of an A320 fixture and crane system. The designs originate from the early 1980s when the aircraft was launched. All assembly operations take place in the fixture which requires all equipment, labour force and components (2000 structural components excluding fasteners) to be used in the same place. This means the design and operation is extremely complex and each operation has multiple dependencies. The system is difficult to upgrade with new technologies because a change to an operation results in changes to several other areas which writes off any cost benefit. Automation improvements are also restricted by access because of all the operations taking place in the fixture. The size, precision and complexity of the A320 assembly system means fixture build and commissioning takes up to 24 months. Each fixture must be certified to ensure the tolerances are with design stipulation. This process takes up to three months and requires production to cease on that particular fixture. Ergonomic access for all operations is also a factor which adds to the complexity of the structure and process planning. Spars and skins are loaded using cranes and straps and manipulated manually into the fixture (Figure 9). Spars, covers and inboard ribs are compliant and deflect out of tolerance under their own mass (Figure 9) which adds to the assembly difficulties.



Figure 7. Image of fixture taken from ground floor. Fixture height is approximately 8m. Note overhead cranes used to load wing structure

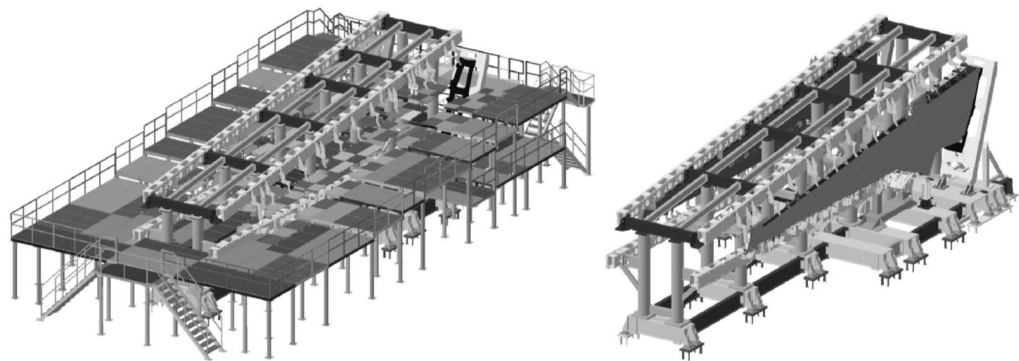


Figure 8. Vertical wing fixture with and without staging



Figure 9. Skins deflect out of tolerance during loading (left) which then have to be manipulated manually into position in the fixture (right)

2.1.3.2 A350 Fixtures

The A350 program was launched in its current form (XWB) in 2006 to replace aging 330 and 340 and compete with more efficient 777 and 787. Wing assembly began in 2011, planned test in 2013 and delivery early 2014. Production was delayed then delivered in 2015 (North Wales Daily Post 2012; Airbus S.A.S 2013; Airbus S.A.S 2015b). The A350 wing assembly is the newest certified Airbus wing assembly facility and represents the state-of-the-art for Airbus. The A350 wing is assembled horizontally in a pulse-type assembly line with major subassembly operations taking place across five stations where each station is dedicated to producing one subassembly (Figure 10). Drawing from A320 lessons learnt, the A350 ramp-up strategy is to ramp-up by beginning with manual assembly for low volume, leaving automation equipment dormant. Wings are assembled manually in each station, mimicking a static build for early low volume production. As production rate increases automation is commissioned and becomes a hybrid of manual and automated processes. Full production rate uses all automated systems and the wing is transferred between cells by AGV. Large gantry-type machine are used for the temporary fastening, drilling and final bolting. The gantry machines require large investment for design effort and operation because of size, precision and complexity. Despite the complexity the capacity is fixed so there is no capacity for rate increases past rate 13 should there be a spike in orders. The large dedicated gantry systems have caused delays to production due to problems with wing drilling (North Wales Daily Post 2012).



Figure 10. Image of an A350 assembly cell showing ribs assembled to front and rear spars. The ladder structure is lowered onto an AGV and moved to the next cell for cover drilling using a gantry machine (top left) (Airbus S.A.S 2015b)

2.1.3.3 Assembly Costs

Assembly systems represent a significant percentage of the production costs due to their fundamental role in the construction of the aircraft. Various sources indicate design, manufacture and operation of assembly systems make up 25-50% of the total production costs. Campbell Jr (2011) accrues structural assembly to 50% of total part cost. Similarly, Coleman (1991) attributes 25-50% of total manufacturing costs to assembly. Bullen (1999) and Mas *et al* (2013) state assembly consumes 40% and 30% of final production cost respectively. The wing fixture itself requires considerable portion of assembly cost because the efforts to design and build. 10-20% of total assembly system cost is dedicated to satisfying fixture requirements (Kihlman 2001). Note that, these values don't specify aircraft model or rate. Gantois & Morris (2004) assign assembly costs as 15 to 40% of total manufacturing costs based on data acquired from Airbus, NASA and RAND Corporation. Their research is the design of a civil aircraft wing optimised for weight, drag and cost.

Journalist sources report the total costs of wing assembly factories to be in the order of millions ranging from £250-650 million¹. In 1990, £250 million was approved for the 150 seat A320 production launch cost after request for an initial £437million (Flight International 1984). The A380 wing assembly factory cost in region of £350 million, launched circa 2002 (AXIS 2015). More recently, the A350 assembly line was reported to be a £400 million facility (BBC 2011). The latest wing factory belongs to Boeing for the 777X aircraft where the wing plant is estimated to cost £650 million (\$1 billion) (Chicago Business Journal 2015). Capacity, factory cost at launch and programme launch are presented in Table 3 for civil aircraft.

Table 3. Capacity, wing factory cost and year of launch for civil aircraft

Aircraft Family	Factory Capacity (at launch)	Wing Factory cost	Programme Launch Year
A320	98 per year	£250 Million	1984
A380	48 per year	£350 Million	2000
A350	156 per year	£400 Million	2006
777X	120 per year	£650 Million	2013

2.1.4 Detailed Explanation of Ramp-Up

The A320 programme was launched in 1984 succeeding design with an order book of 96 aircraft and an original business case for 600 aircraft (Airbus UK 2012). Maximum capacity was 98 aircraft per year. Planned ramp-up was as follows: 1988: 30, 1989: 50, 1990: 66 (Flight International 1984). In 1986, A320 delivery slots were sold out until 1991 (Flight International 1986). Prior to first flight and delivery in 1987, 750 aircraft were predicted to be in service by 2005 (Flight International 1986). In actual fact, in 2005 2,631 aircraft were delivered and 2070 were on back order (Airbus S.A.S 2016a). The fixture method of assembly was unable to ramp up fast enough and meet demand.

Ramp-up is the increase in aircraft production rate. The current method to ramp up production is to build additional fixtures on receipt of new orders. Wing assembly is one of the most intensive to ramp up. Tolerances are higher than fuselage because of the landing gear and flap mechanisms across large distances. Ramp-up is also hampered compared to fuselage because of the production of port and starboard wings. Main assembly fixtures take up to 24 months to build and commission due to their size and the complexity of the assembly process (Millar & Kihlman 2009; Williams & Airbus S.A.S 2009). This delays aircraft delivery to the customer. In the meantime new orders come in and delays delivery further.

¹ Values converted to GBP. USD to GBP conversion rate: 0.64£ = 1\$.

2.1.4.1 Ramp-Up Definition

Production ramp-up is a crucial phase in product lifecycle which involves the inaugural manufacture of a new product for market entry. Ramp-up is defined by Terwiesch & Bohn (2001) as the period between 'the end of product development and full capacity production'. In aerospace, the term is also used to describe subsequent production changes where production rate of a current model is increased (Millar & Kihlman 2009). The thesis uses the latter definition when referring to ramp-up.

During ramp-up periods, systems demonstrate insufficient capacity against market demand. The time taken to achieve full production volume limits product deliveries and therefore revenue payment. Delayed ramp-up may even result in order cancellation or loss of market share. The issue is compounded further still when additional orders during ramp-up put increased strain on capacity leading to back log. As a result, the system cannot keep up with market demand and revenues remain unclaimed. This section focuses on ramp-up in terms of increasing production rate by adding additional assembly systems. The Airbus method to ramp-up wing assembly production is described and analysed in relation to orders and deliveries.

2.1.4.2 Current Airbus Ramp-Up of A320 Wings

The method of production ramp-up for A320 is to build and commission duplicate fixtures. This approach has been applied from the outset of production with rates of 4 per month to the current production rate of 42 per month. Ramp-up is initiated by decision-makers based on the order book. The number of fixtures to be built is determined and contracts are distributed through the supply chain. The fixtures are then built and the tolerances certified for production. A labour force is trained and deployed to begin wing production. The ramp-up process can take in excess of 24 months to reach the new capacity. Fixtures cost approximately £10million in NRC as well as the required floor space which carries its own costs. Each additional fixture increases production rate by approximately two extra aircraft per month. The number of fixtures that can be built for ramp up depends on many factors beyond the scope of manufacturing engineering but is largely limited by available engineering resource. Building fixtures is a major operation which requires dedicated support from design, manufacturing and procurement as well as the involvement of certifying bodies and the supply chain. Historical data presented in Figure 11 indicates that the maximum ramp up occurred in 2000 where production increased by 10 aircraft per month where fixture building began as early as 1997 where orders began to increase steadily until 1999. 2001-2003 saw a lull in orders due to the downturn of people wanting to fly after four aircraft were hijacked by terrorists and used in suicide attacks on the United States (Airbus S.A.S 2016b). In 2004-2008 orders increased dramatically from the lows of roughly 150 to orders in excess of 700 per year. Production increased by 8 per month by 2006 and increased by two per month thereafter, limited by resources to commission new fixtures; until the financial crash of 2008. 2012 saw record orders of 1473 up from 228 in the close of 2009. Again, the system had difficulty ramping up production to respond to new orders and as of 2014 the backlog was 6193. Airbus orders and deliveries data presented in Figure 12 shows the extent of the problem. The order backlog has accumulated because assembly systems cannot cope. Certainly, a small percentage of manageable backlog is acceptable for business outlook. However, a backlog of 6193 aircraft represents approximately €400 billion in revenue. Airbus forecast demand for 22,071 single-aisle passenger aircraft between 2014 and 2033 including the current backlog. Ramp up needs significant improvement to cope with forthcoming demands for assembly.

Ramp-up considerations early in design can become major constraints on aircraft delivery through life. A320 backlog is directly linked to assembly system design where the original design cannot cope with new demand. Ramp-up should be a clear requirement with greater consideration in future ASD. A future RASDM should possess this capability and enable designer freedom to associate this with RAS scalability function.

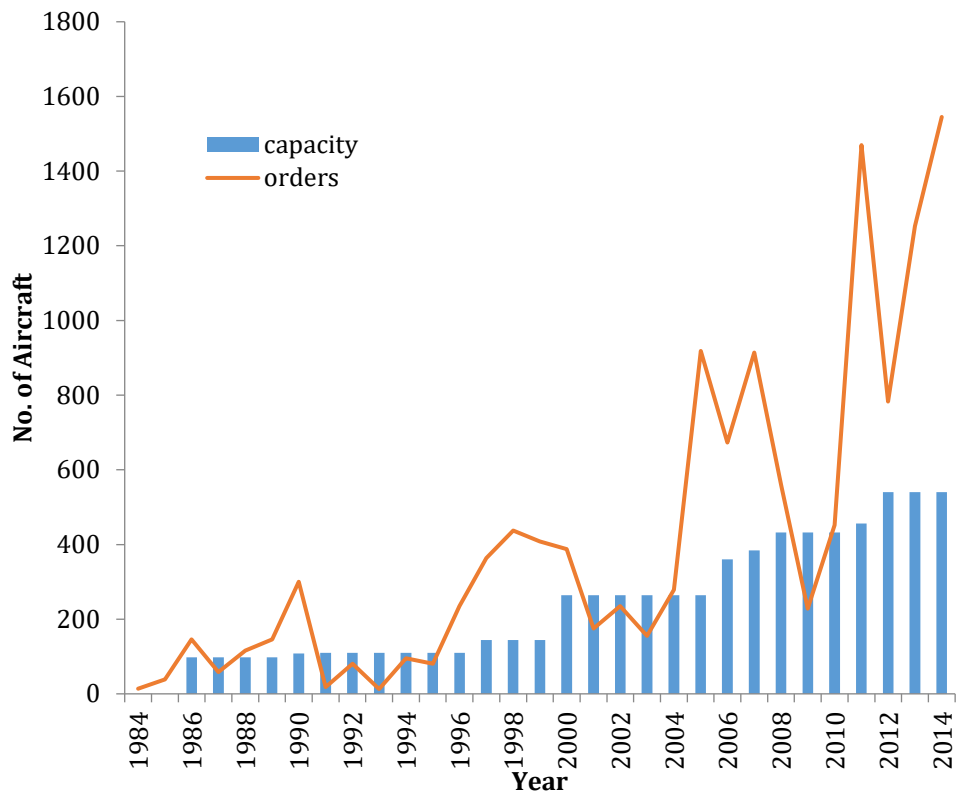


Figure 11. A320 Factory Capacity and Orders for years 1984-2014. Source: Airbus 2016a; FlightGlobal 1984-2015

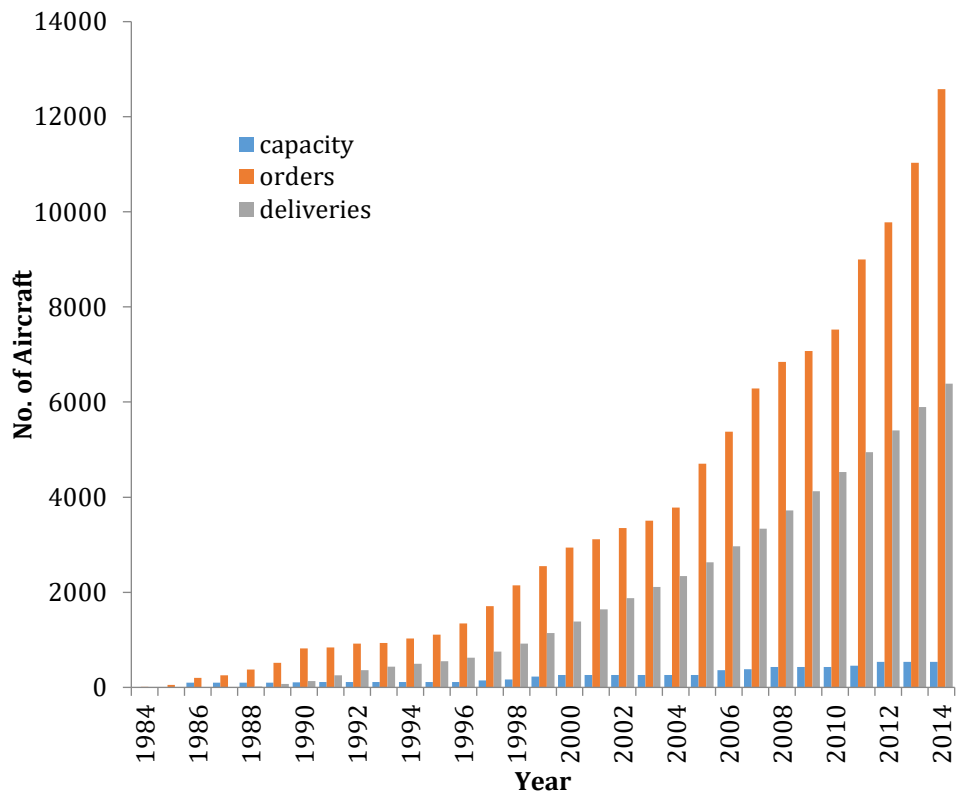


Figure 12. A320 factory capacity and orders and deliveries for years 1984-2014. Source: Airbus 2016a; FlightGlobal 1984-2015

2.1.4.3 Pulse Line

The A350 went into production in 2006 and uses a 'pulse line' assembly method. The spars and ribs are located and fastening in one cell then 'pulsed' to the next cell for lower cover drilling and so on, much like a conventional assembly line. The A350 ramp up method is two-stage where for low volume production wings are assembled manually in each station, as per a static build. Automation is in place for the system to increase production rate by automating drilling and fastening and AGVs are available to move the wings between cells. The gantry machines require large investment for design effort and operation because of size, precision and complexity. Despite the complexity the capacity is fixed so there is no capacity for rate increases past rate 13 should there be a spike in orders. Modifications to add elements or change structure to reduce cycle time require extensive modification to the system because of the structural connectivity between elements. Ramp-up to automated production takes 6-12 months but the automated drilling system had difficulties in deployment because of its complexity and automated production was delayed. Rates higher than 13 will require a new production line and facility which will take over 4 years to commission, in which time orders will accumulate. This approach is currently being used for a new A320 pulse line which is being built. The system ramps up by adding additional lines which take over 12 months to commission. There are some similar 'rate enable' capabilities to move from manual to automated but is only in a few cells in the line and so does not improve delivery rate. Each line produces wings at a rate of approximately 15 per month and all three lines in use are expected to achieve a rate of 45 in addition to the existing A320 fixtures.

2.1.5 Limitations of Current Wing Assembly Ramp-Up

The current ramp-up methods are not sufficiently scalable for increases in demand. Airbus production data presented shows this to be the case. The backlog caused by slow production ramp up restricts net revenue. Building new fixtures or production lines takes over two years, in which time orders are still accumulating, rendering the system under capacity on completion. Ramp-up is too slow to respond effectively to market changes which means unnecessary investment in extra capacity when orders drop unexpectedly. Equally additional orders soon exceed the planned capacity increases contributing to backlog i.e. planned production increases are midway when there is a drop or spike in orders. The A320 rate of increase of 120 wingsets per two years is too slow to meet demand which has caused a backlog of 6193 at the close of 2014. Estimated to be worth €400 billion in net revenue.

Current ASDs date back to the early 1980s when designers were more concerned with achieving the design tolerances on wing assemblies with limited tooling and machining capabilities. Hence, the assembly systems are of fixed monolithic design with little interchangeability. Systems were designed for a fixed capacity because low volumes were expected and ramp-up was not a major consideration. Design has not given consideration to structural independence for changeability. Changes to the assembly systems to improve production rate are unfeasible because of the interdependence of the substructures. Wing assembly systems designed with ramp-up in mind to change in structure and could quickly increase capacity by adding automation.

2.1.6 Model Change

Airframers compete to produce the most efficient product in terms of airline operating cost and production cost. Continual development of technologies in aircraft design and manufacturing mean aircraft and manufacturing processes are soon outdated. Pressure to reduce costs from airline operators have forced newer, more efficient models to be introduced which has resulted in extensive modifications to the production system. The modifications have been costly to implement because the fixed design of the system means changes affect several areas of the assembly system. Indeed, this is also evident for new manufacturing technologies which cannot be implemented because of the interdependent structure of the ASD.

Airline operator costs are dependent on fuel cost. Therefore key areas for improvement are aircraft mass, aerodynamic performance and fuel burn efficiency. Aviation advances in material science, aerodynamics and computational analysis contribute to new efficient solutions which make current efforts redundant. The increased use of composites and new efficient engines have had arguably the most prominent impact on manufacturing and assembly. Implementing changes to both aircraft design and manufacturing and assembly techniques disrupt current production. Changes to the design or assembly process are usually triggered by demand from a drop in orders or a market opportunity, generally found by market analysis. The two most recent modifications to the wings of Airbus aircraft are the re-engined A320 and the transition to -1000 for the A350. Both required considerable investment and time to implement.

2.1.6.1 A320NEO Modification

The A320 fixtures required modification to respond to market demand. A320 was launched in 1987 and has seen unexpected longevity but now has dated technology. Market analysis anticipated new-engined C-series from Bombardier which has greater efficiency and is competing directly with A320. Airbus were forced to respond with an updated design (Figure 13) but the fixture was only designed for one model and not designed to be easily modifiable. Despite less than 5% change in the wing structure fixture modification was greater than 5% and took approximately 4 years (The Flying Engineer 2014).

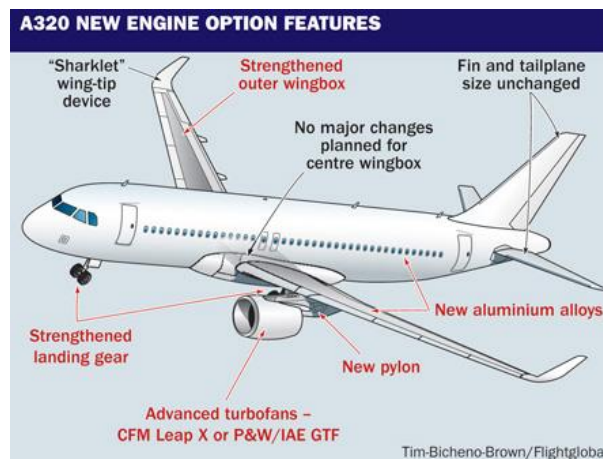


Figure 13. Changes made to the A320NEO (Flight Global 2010)

2.1.6.2 A350 Modification

Similar issues exist on the A350 assembly line where the fixture designs are fixed with little consideration given to modularity. The A350-900 production began in January 2015 and a second model: A350-1000 is expected in mid-2017. The key changes for A350-1000 are presented in Figure 14. The changes to the wing structure are relatively minor but due to the design of the assembly fixtures the modifications are expected to take up to two years. The fixtures are not readily changeable for the minor differences in models. The program is also compounded by technical delays. The accumulation of delays has resulted in some orders being cancelled.

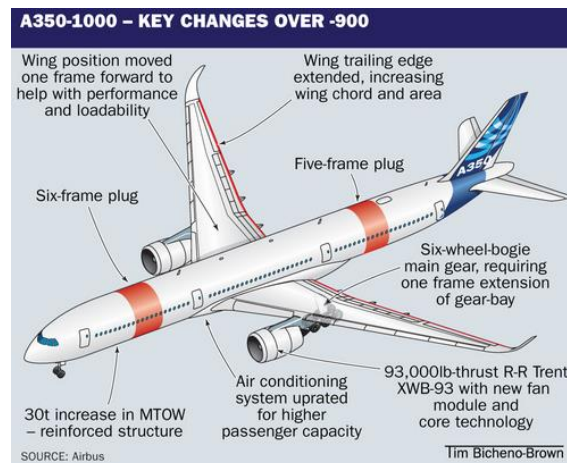


Figure 14. Key changes to A350-1000 compared to A350-900 (Flight Global 2014)

2.1.6.3 Limitations of Current Model Change Methods

The coupled structures and substructures in the assembly systems require modification which extends beyond the product-tooling interfaces because of the physical coupling of elements in the fixture structures. This results in lengthy modification to the system for minor changes in wing design. Design of a more modular system could shorten the time and costs necessary to make modifications to the system for new wing models.

2.1.7 Summary and Critique for Transition to RAS

Assembly is a complex process crucial to the safe function of the aircraft and incurs considerable portion of the total costs. The assembly process is strictly controlled. The combination of tight tolerances and large compliant parts make assembly difficult and time-consuming. The assembly fixtures are dated, monolithic structures which not designed for ramp-up which has contributed to a large backlog of orders.

The limitations of the current assembly systems point to a number of implications which must be addressed to transition to a RAS for wing structures. Firstly, the assembly systems as they exist today aren't designed to rapidly change in structure. The systems have interconnected elements which prevent incremental increase in production rate and necessitate construction of entirely new lines to increase capacity. This process is costly and time consuming and has contributed to a significant backlog of orders. If the systems were designed from the outset to be scalable and customisable in structure then capacity could be increased incrementally without the need for duplication of production lines. With careful design this could be a much shorter process which would result in a smaller backlog. The RASDM must enable the designer to specify systems to be scalable and customisable and a greater level of independence is needed between elements in the system structure. Decoupling the system design into a more modular structure should enable quicker change because of fewer modifications. This should be a specific function of the RASDM. The requirements for rate and ramp-up should also be included in the RASDM to yield detailed designs that are physically able to change in structure to increase capacity or produce new models. Certainly, this is difficult given the unpredictable nature of market demand and the types of changes that will be needed. A RAS which changes is likely more complex than the current static system so the design needs careful management so as to satisfy the requirements. In regard to implementing and RASDM at Airbus, changes to the design stage are needed where ramp up is given more consideration and independence can be specified in the requirements of the system structure.

2.2 Current Design Practices at Airbus

This section deals with designing a RAS for future aircraft wings within the Airbus organisation. A study of current design practice is carried out in order to understand how to transition from DML design to designing RAS. The intention is to design RAS for Airbus wings which means using Airbus design infrastructure and documentation as well

suitability for certification. The study forms the basis of partial requirements for an Airbus RASDM and guides the search for a suitable DM. The focus of the review is factory design and manufacturing and so particular practices relating to aircraft design are not considered where independent of manufacturing.

Airbus apply concurrent engineering to shorten the development phase of aircraft and improve time-to-market. This is achieved by overlapping the design and industrialisation processes. This means design considers multiple aircraft configurations which must be industrialised. Industrialisation must consider different design configurations and generate solutions for each configuration. This generates large volumes of data which is subject to change. Large amounts of knowledge are also generated in early stages as a by-product of this. This knowledge is used by designers in the industrialisation process. The process of capturing knowledge from aircraft design is incremental. Industrialisation must use changing and often incomplete data to conceive assembly system solutions. A RASDM must operate according to these Airbus practices to produce designs which are suitable and based on meaningful Airbus requirements. The review of design practices is based on observations during projects, internal documentation, discussions and academic literature.

2.2.1 Airbus Concurrent Design Method

Aircraft design is a deeply complex multidisciplinary task that must satisfy customer requirements as well as airworthiness authorities (Pardessus 2004; Ledermann et al. 2005). The process is a top-down approach and begins with an aircraft configuration to satisfy a market niche or the requirements of airline operators. Aircraft have typically long lifecycles with careful market analysis and supporting work taking place years before committing capital to program launch which adds to the program costs. Supporting work is considered anything contributing to the final aircraft which is typically market analysis and R&D for innovation, design feasibility and technology maturation. Table 4 presents the program costs and launch dates of in-production aircraft. Ten years of work contributed to the A380 project prior to program launch (Airbus S.A.S 2005; Bhaskara 2015; Norris & Wagner 2005). Similarly, four years' work was carried out for a single-aisle aircraft which became the A320 in 1981 (Flight International 1984; Aviation News 2014; Payne 2004). Newer aircraft such as the A350 and C-Series have program launch to first flight similar in length to the earlier A320 and A380 but shorter time between project announcement and program launch, possibly due to strategic reasons or changes in business structure (Airbus S.A.S 2013; Reuters 2009; BBC News 2004; Bombardier 2004; Marowits 2015).

Table 4. Aircraft development costs

Aircraft	Program Cost	Project announced	Program launch	First flight
A380	\$15 Billion	1990	2000	2005
A350	\$15 Billion	2004	2006	2013
A320	\$2 Billion	1977	1981	1987
C-series	\$5.4 Billion	2004	2005	2013 (CS100)

The billions of capital invested and the ten years or more between program launch and first flight means companies do not see ROI for tens of years. All phases of development are scrutinised to reduce time-to-market and quicken ROI, particularly design and manufacturing which make up the majority of an aircraft program. Airbus S.A.S use concurrent design to shorten design and manufacturing phases. Figure 15 presents a traditional, concurrent and collaborative view of aircraft development.

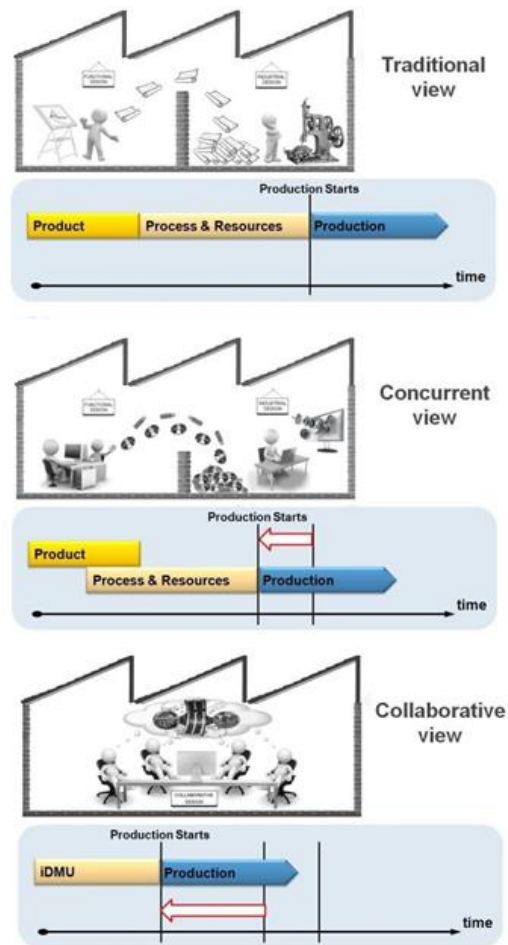


Figure 15. Three views of the aircraft development process. The traditional view observed sequential development of product and processes which then became overlapped for the concurrent approach. The latest method is all engineering disciplines collaborating on a single digital mockup which goes into direct production (Mas, Menéndez, et al. 2013)

The principle of concurrent engineering is the overlap of product design and industrialisation. Such that, industrialisation begins before aircraft design is frozen. Thus there is iteration between the design and industrialisation where one may influence the other based on noted benefits. Concurrent design is enabled by CAD and PDM systems where data is updated during development (Ledermann et al. 2005). Design is an important stage as it determines the cost of the aircraft. Between 60-85% of the final aircraft cost is determined by the design phase (Mas, Rios, et al. 2013; Willcox 2004; Syamsudin & Fielding 2004). It is therefore necessary to arrive at a satisfactory design as soon as possible by managing the iterations. Periodic reviews are used to manage these design-manufacture iterations. Airbus use a milestone method for development where each milestone has a description of the expected status of the aircraft program which is used for progress comparison and planning work for the next milestone (Figure 16). Actual work to achieve each milestone is a multidisciplinary mixture of R&D, design, strategy and re-evaluation of market and objectives. Figure 17 shows the overlap between aircraft design and industrialisation. In upstream processes (M0-M7) (concept, feasibility, preliminary definition), processes are highly interactive and iterative. Changes are more frequent and must be managed carefully in order not to be frozen too early (M7). Work is mainly focused on architectural level, and trade-offs are frequent with a high impact on the configuration (Pardessus 2004). In the development phase (M8-M14), changes are limited to very local design and industrial performance (Pardessus 2004). A future RASDM should be applicable in a similar manner and changes to procedure should be minimised.

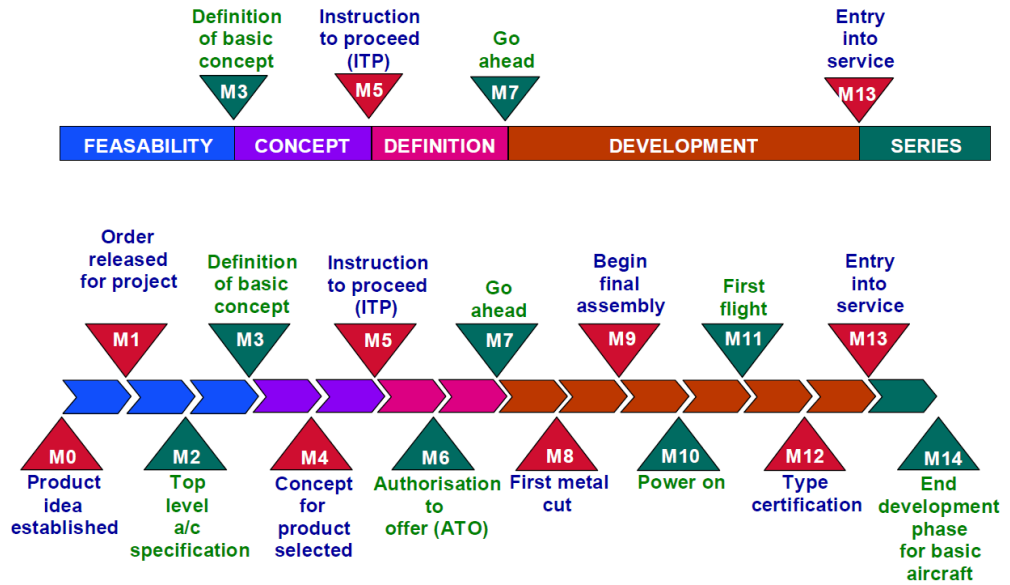


Figure 16. Airbus aircraft development milestones (Pardessus 2004)

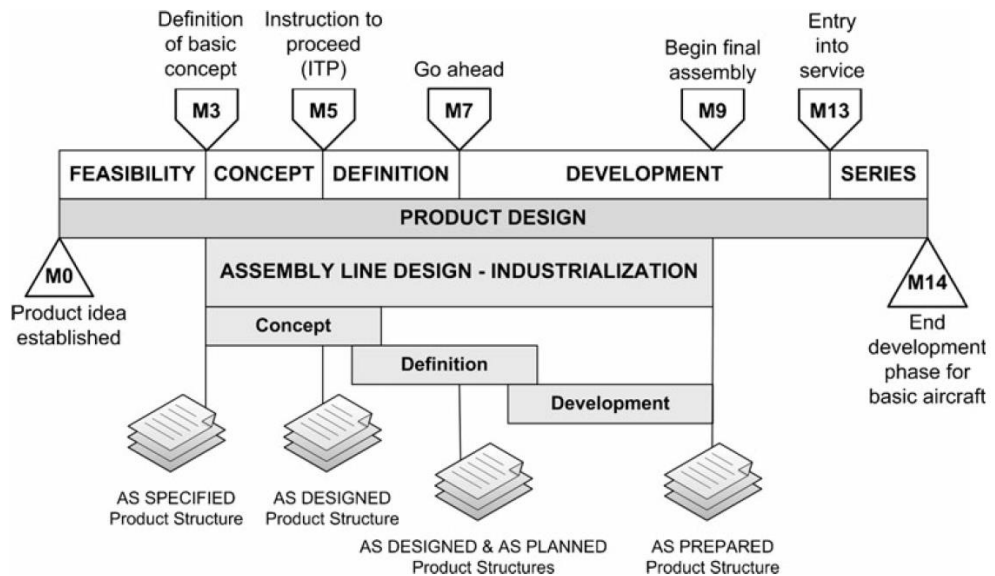


Figure 17. Typical Airbus aircraft design lifecycle where product design and industrialisation overlap (Mas, Rios, et al. 2013)

2.2.1.1 Design-Manufacture Iterations

The iteration between aircraft design and industrialisation is not easy in practice because of the requirements of stakeholders across multiple departments (Ledermann et al. 2005). The complexity is also compounded by design changes and propagating manufacturing options. Aircraft design is optimised for efficient flight characteristics and scenarios. Early stages of design are subject to more changes so industrial design has to concede to design (Schieck et al. 2002). Figure 18 presents typical concurrent aircraft and industrialisation design tasks. A future RASDM should be inclusive of these iterations and indeed use this design information to define the reconfigurable capabilities of the assembly system.

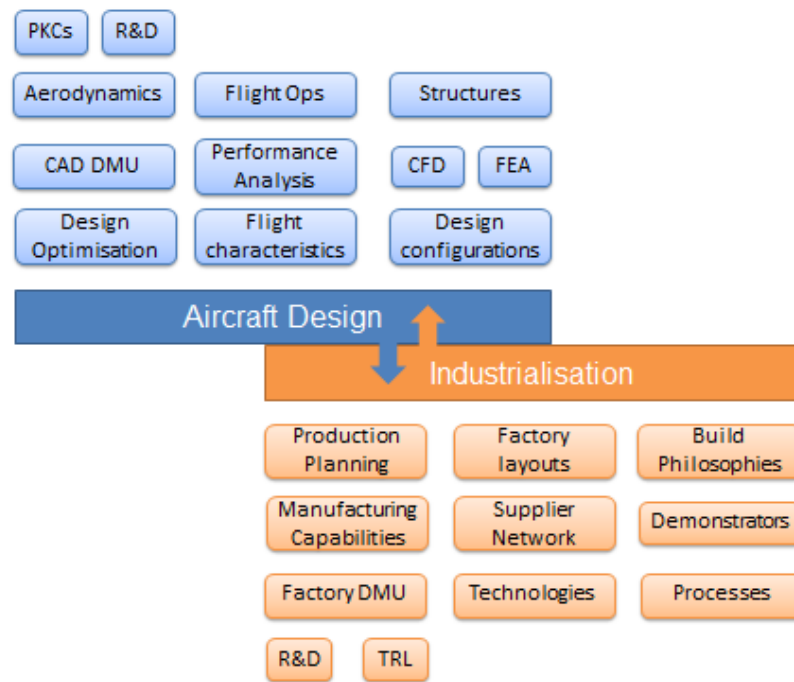


Figure 18. Concurrent aircraft design and industrialisation processes. Many tasks require collaboration and information is fed back and forth between engineers.

Each aircraft configuration typically has a number of manufacturing options with various advantages. Each aircraft structure or component also has a number of options which are compatible with a particular configuration. Figure 19 presents a typical situation where an aircraft configuration has a number of options for a major structure, in this case fuselage. The Industrialisation process develops solutions for each configuration with respect to these design options. The design changes through the course of aircraft development and so the industrialisation also has to change. This generates large volumes of design tasks and data that has to be optimised.

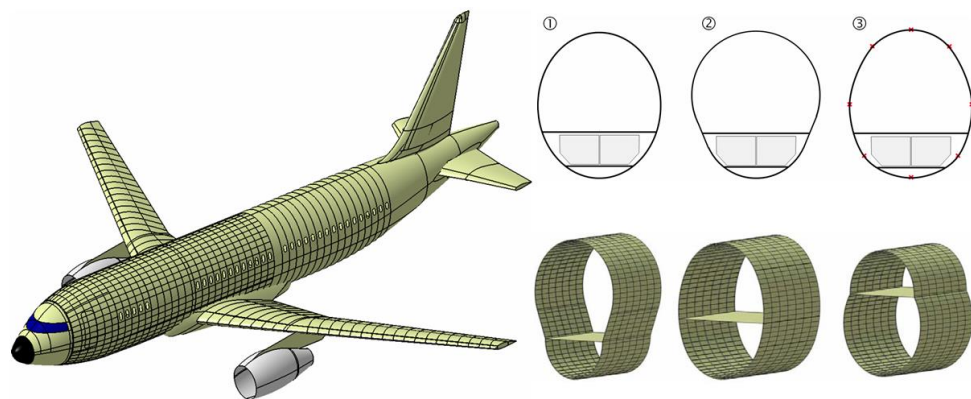


Figure 19. Preliminary aircraft design model for assessing various geometric configurations. Industrialisation must use this changing data to form and assess assembly solution options in parallel. Industrialisation may also influence geometric configuration in certain cases (Ledermann et al. 2005)

Figure 20 depicts a typical scenario where three likely configurations of aircraft each generate three possible ASDs. The aircraft configurations share some commonality. Each aircraft configuration may potentially become the final aircraft design. Industrialisation has to consider optimum production of each configuration. The uncertainty of the design data means design changes frequently occur and ASDs require modification where there is no commonality between solutions. The multitude of industrialisation options and frequent design changes means the industrialisation is a complex process.

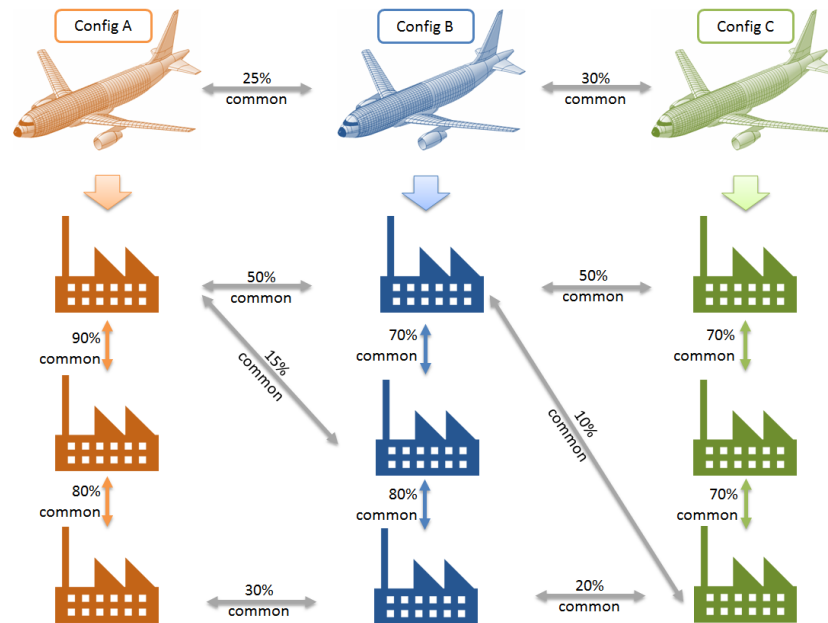


Figure 20. Aircraft configurations generate numerous industrial solutions with varying commonality, creating large volumes of data to be analysed for decision-makers

Figure 21 presents an Airbus example of industrialisation options for each aircraft configuration which must consider multiple R&D programs for both aircraft components and manufacturing technologies. This generates large amounts of data. A number of activities are carried out within each milestone. The Airbus concurrent engineering approach integrates sociological and technological aspects and multiple engineering stakeholders must participate in a consensual joint decision making process (Mas et al. 2014). The collaboration between engineers is knowledge-based because of frequent iterations and the milestone approach is used to collate a freeze design solutions (Mas et al. 2014). The RASDM should enable collaboration and function effectively in this knowledge-based environment.

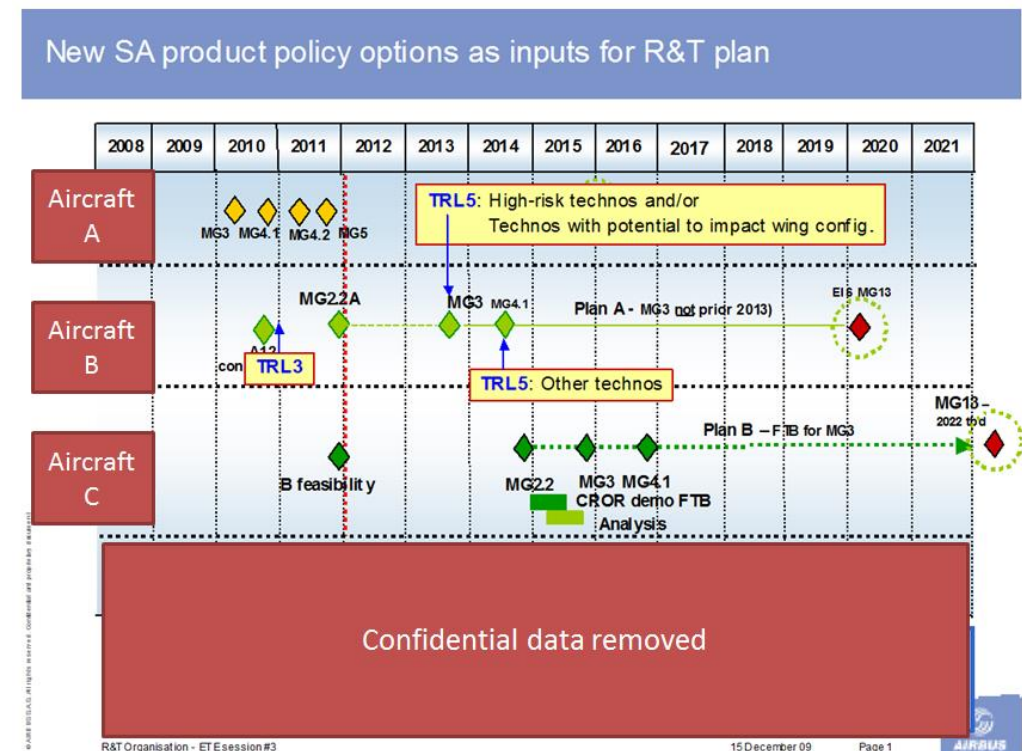


Figure 21. Industrialisation options and milestones for three potential aircraft configurations (Airbus UK 2009c)

2.2.1.2 Airworthiness Certification

Aerospace is quite probably the world's most demanding industry in terms of ensuring that the final product is exact to the designer's specification and intent. The cost of deviation from design is high both financially and in terms of human life. Not only must the final product be correct, it must be shown and proven to be correct throughout its manufacture. These stipulations are brought to bear by the aviation authorities that legislate for, and police all aspects of aviation. Certification is costly and time consuming so is more efficient to reuse processes. Since most aerospace design is knowledge-based this knowledge needs to be used as input into design.

The certification involves exhaustive testing and validation to comprehensively prove the safe operation of the aircraft. Each manufacturing process is tested and validated to ensure its repeatability. Validation must be traceable through all stages of design and manufacturing. Certification is extremely time-consuming and costly and even minor changes to geometry or manufacturing processes require recertification (De Florio 2010). Airbus aim to reduce certification costs by 50% by 2050 (Airbus UK 2012; Krein & Williams 2012). An excerpt of passenger aircraft certification documentation is presented in Figure 22. Virtually all modifications to any part of the aircraft or the manufacturing process require recertification. For composite components, material changes extend so far as to include environmental parameters. Such is the depth of analysis required to meet airworthiness safety which must be a fundamental consideration of transition to RAS design.

Modifications					Verification Testing		
Case	Geometry	Material	Process	Foundry	Qualification of Process	Proof of Product	Tests per CS 25.621(c)(1)
1	yes	none	none	none	not necessary	yes	yes (b)
2	none	yes	none	none	yes (a)	yes	yes (b)
3	yes	yes	none	none	yes	yes	yes
4	none	none	yes	none	yes (a)	yes	yes (b)
5	none	none	none	yes	yes (a)	yes	yes (b)

Figure 22. Recommended verification testing for qualifying changes to aircraft component or process (EASA 2013)

Wing certification takes up a significant part of the certification process due to its size. The wing has to be proven to withstand 1.5x maximum loads measured in and support this without failure and have safe operation for 3 seconds and all loads such as fuel mass must represent actual conditions (EASA 2013). Airframers must evidence means of compliance which includes all design process documentation, calculations and analysis and testing information. Figure 23 presents the structural testing of the Boeing 787 Dreamliner wing. The wing structure is monitored at key points with thousands of sensors and strain gauges to observe the structural performance of the wing. The costs of certification often prohibit introduction of new manufacturing technologies which is compounded by the assembly methods. Whole new fixtures require certification for only minor process changes because of the interconnected design of the fixture. This has led to manufacturing systems remaining unchanged and has led to a conservative approach in design where already certified methods are used to reduce time and cost. The conservative approach to design restricts innovation and technology insertion which offers savings to the operator (aircraft and manufacturing technologies). A more independent design is less costly to change so costs are more viable for recertification. New processes require lengthy and expensive certification, aim should be to minimise this whilst remaining open to novel solutions (Holmberg et al. 2004). The primary method of design is tacit knowledge and so certification knowledge is with engineers. The highly collaborative and complex nature of aircraft development means the primary source of design information is the tacit knowledge of engineers (Mas et al. 2014). What is needed is a design approach that considers certification in the early design phase but remains open to innovation, allow the designers freedom to consider novel technologies.

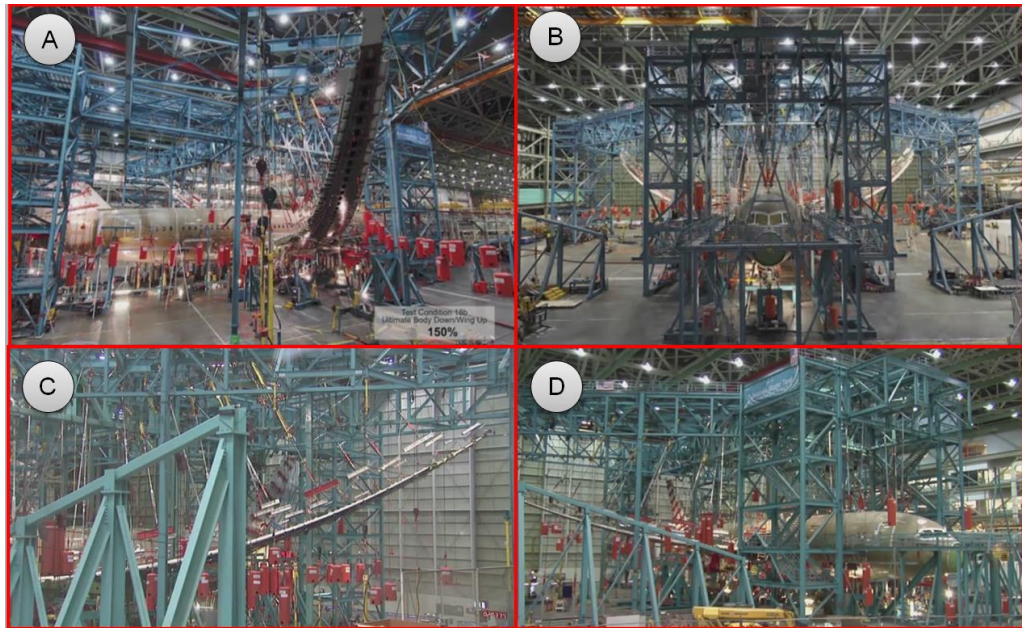


Figure 23. Structural testing of Boeing 787 Dreamliner for certification. (A) The wing is stressed to 1.5x maximum flight load. (B) Both wings are stressed to replicate flight conditions. (C) guides and pulleys are used to deflect the wing and distribute the loads as per flight (25 feet) (D) large bespoke structure built specifically to perform structural testing (The Boeing Company 2010)

2.2.2 Industrial Design Activities

The nature of the Airbus concurrent design method means industrialisation has to consider incomplete or changing data. Industrialisation begins in the concept stages of aircraft design, at which point aircraft designers are often considering several configuration options. This means there is iterative process for manufacturing engineers where several options must be developed in parallel. The frequency of design change means large amounts of data needs to be assessed and translated into manufacturing solutions. The decisions made during these design phases in early engineering design are mainly based on the designer's intuitions and previous experience (Li & Mavris 2006). Because of the design data being largely knowledge-based, industrialisation uses collaborative approaches that are ad-hoc and heuristic. Aircraft design and industrialisation is a collaborative, predominantly human-decision process (Mas et al. 2014). Collaboration takes the form of various activities between engineers. These industrialisation activities are reviewed and characterised to select and implement a compatible DM.

2.2.2.1 Knowledge in Aerospace Industrial Design

Aerospace is a highly collaborative, knowledge-intensive industry. The knowledge is dependent on the legacy systems and approaches within the industry. The UK aerospace industry has developed a core competency in aerostructure assembly which has been developed over many years and from vast experience. This has resulted in a particularly knowledge-intensive product development process and placed great dependency upon this knowledge base (Roy & Williams 1999).

Aircraft design is an ongoing state of change during the development phase. The primary source for industrial design is designer knowledge because of the iterative collaboration between design and manufacturing engineers. Due to this fact, designer experience and knowledge is central to industrialisation activities. The designer's experience represents a crucial portion of the information which has to be made available (Bley et al. 1996). Because of the large volume of data generated, much of the knowledge is tacit and based on experience (Baird et al. 2000; Zawawi et al. 2010). Much of the designers ability is tacit knowledge built incrementally through experience (Hickie 2006). Industrialisation is a complex process because of dynamic changes and large number of design tasks. The iteration between aircraft design and industrialisation is not easy in practice because of the requirements of stakeholders across multiple departments (Ledermann et al. 2005).

The development of aerostructures involves the application of huge amounts of knowledge, information and data. (Roy & Williams 1999; Ledermann et al. 2005). Industrialisation has to extract this knowledge and assess and translate into factory design. Data has to be elicited through workshops and discussions, captured then the progress reviewed in the design milestones. Data is often ambiguous or incomplete for ASD. As a result, industrialisation and ASD has to use approaches that are ad-hoc and heuristic which can lead to less optimum solutions. The industrialization at the Conceptual Phase has not been supported by predictive technologies as much as the aircraft development (Mas et al. 2012). The design of aerospace assembly lines is characterized by a collaborative way of work, where several industrial partners are involved, and personnel knowledge and competencies are its main support (Mas et al. 2012).

The following sections discuss each of the main industrialisation activities particular to ASD. The manufacturing R&T program is also discussed since RAS will be developed according to the Airbus TRL maturation methodology. The review highlights the ASD practices to guide a review of academic literature search for relevant design methodologies for RAS design. Design activities are also reviewed to determine data types.

2.2.2.2 Manufacturing R&T Program

The review of design activities is focused on Airbus Manufacturing Research and Technology (R&T) because this is the department that RAS design will operate in for this research. The main function of R&T is the systematic risk reduction and maturation of novel research and technologies. To stay ahead of competition, Airbus must deliver the most efficient, innovative aircraft. To achieve this, Airbus expects R&T Program to provide novel technical solutions to advance the state-of-the-art in aerospace. Airbus relies on the R&T Program to secure systematic risk reduction for introduction of R&T Products into Business. As such, maturity is considered as the result of identification and then mitigation of technology developments' impact on: Performance & Integration, Engineering, Manufacturing (including industrialization), Operations, Value & Risks (Airbus S.A.S 2012). Airbus R&T uses a TRL-based methodology and associated systematic risk reduction approach. This methodology is applied to all research and can be 'an architecture, a system, a subsystem, a component, as subcomponent, a major assembly, a capability, an elementary technology, a tool, a methodology, a specification change' (Airbus S.A.S 2012). Collaborative engineering activities are carried and at each milestone a gate review procedure is followed. The technology must pass all the Airbus TRL criteria to proceed to the next level of development.

2.2.2.3 Airbus TRL Methodology

The Airbus TRL methodology is based on the original NASA definitions but uses a greater scope to suit Airbus business needs to bring systems to production maturity. It has been designed specifically for procurement and as a systematic approach of risk-reduction management. Progression through each TRL is subject to a gate review with all stakeholders. Engineers work to reach milestone requirements. A large amount of engineering research and development goes on in between milestones to bring products and processes to maturity. The overall approach is usually iterative and built on existing knowledge, lessons learnt and previous R&D work. The main activities to build knowledge and conduct R&D are technical workshops, benchmarking, build philosophies, technical reports and physical demonstrators. Once sufficient work is carried out the gate review procedure against set criteria designed to mature and develop the product. A gate review involves all stakeholders in the project and evidence and demonstrations are presented for each criteria statement in five categories which are Performance Readiness, Engineering Readiness, Manufacturing Readiness, Operations Readiness and Value and Risk. An example of TRL2 criteria is presented in Figure 25. The RASDM must use the existing TRL process to minimise business impacts. Technologies and systems supporting RAS capabilities must also progress through the TRL methodology.

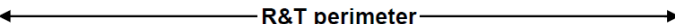
EADS shared TRLs									
Description	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof of concept	Component and/or breadboard validation in laboratory environment	Component and/or breadboard validation in relevant environment	System/sub-system model or prototype demonstration in a relevant environment	System prototype demonstration in a operational environment	Actual system completed and "flight qualified" through test and demonstration	Actual system "flight proven" through successful mission operations
Definition	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development	Invention begins. Once basic principles are observed, practical applications can be inverted. The application is speculative and there is no proof or detailed analysis to support the assumption	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness	Prototype near or at planned operational system. Represents a major step up from TRL6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation
AIRBUS Maturity Phase	Discover		Understand	Adapt		Validate	Refine		
 R&T perimeter									

Figure 24. Airbus TRL Methodology descriptions and definitions. R&T is directly responsible for TRL1-6 and oversees handover for TRL7 stakeholders (SESARJU 2015)

The TRL process is usually documented using PowerPoint format for ease of communication to stakeholders in a collaborative environment and any supporting documentation is referenced. Each category is marked conclusive or not conclusive and the overall TRL review is marked as Proceed, Stop or Redirect.

< Technology Product > TRL2 _ DECISION TABLE			1/x
TRL2 Criteria		Sufficient Work Conducted	Viability Established
Performance Readiness			
Identification of potential applications and asstd reqts on A/C or into Prod. / Manuf. Process			
Set up criteria to select or reject applications			
Screening of new Generic Material or Technology to demonstrate properties of Technology			
Prel. asst of new Generic Material or Technology perf. vs specs and current solution			
Identification of inter-dependencies with other products			
Identification of potential scale-up issues and generation of mitigation plan			
Engineering Readiness			
Identification and awareness of suitable sponsor or target End-User secured			
Identification of concepts for new Engineering capabilities if required and awareness of related relevant stakeholders			
Prel. asst of impact on AIRBUS Engineering (incl. skills, training...) and Supply chain (incl. Extd enterprise reqts)			
Assess potential for Certification issues, contravention of Regulation (A1091, REACH)			
Manufacturing Readiness			
Prel. asst of processes (prod., manuf....) characteristics (small feasibility coupons), incl. Techno difficulties description			
Prel. asst of Manufacturing concept			
Prel. asst of impact on AIRBUS Manufacturing and Supply chain (incl. mono/multi source, ramp-up capability...)			
Operations Readiness			
Identification of repair process key characteristics and associated capabilities			
Prel. asst of impact on Maintainability, Availability, Reliability and Damage detection			
Value and Risk			
ROM Estimate of benefits vs current solution and prel. asst of technical/industrial risks, incl. potential fallback solutions			
Identification of related patents and patent holders			
Assess potential for AIRBUS patents, Intellectual Property issues			
IP Policy proposed according to strategy importance of Generic Technology			
Identification / summary of potential showstoppers (technical) and mitigation assessment			
Route to TRL3 (business case, activities and asstd framework, means of demonstration and availability, level of effort...), according to solutions / implementation options			
Review PASSED / NOT PASSED			
Technology Recommendation PROCEED / STOP / ON-HOLD			

Figure 25. Example of Airbus TRL 2 Review Criteria

The outcome of the TRL gate review is used to plan activities future R&D activities. This is usually the next group of work packages to reach the next TRL gate or carry out additional research. The TRL review process is based on demonstration of maturity through evidences vs. TRL Criteria for traceability of information. All the information and data is discussed and challenged during official TRL Gate Reviews. This process will be followed for the design and implementation of a RAS for a future aircraft.

2.2.2.4 Technical Workshops

Airbus UK relies predominantly on knowledge to develop aircraft (Roy & Williams 1999). Industrialisation is often a heuristic process because of the changing state of the aircraft design. This results in highly iterative collaboration between engineers which often takes place in technical workshops. Technical workshops are a key process for ASD and the RASDM should be use these directly and indeed support designers. The workpackage leader sets an agreed agenda and nominates someone to capture the data. The data is then collated and distributed for review by all stakeholders and then accepted into a final format for future reference. Technical workshops are used to capture knowledge on technical aspects, lessons learnt and existing R&D. They are also used to discuss and critique ideas, particularly crucial in the early stages of industrialisation which are highly iterative and require a lot of designer input because of ongoing development. The designer's experience represents a crucial portion of the information which has to be made available for design (Bley et al. 1996). Data typically has to be elicited from engineers to capture technical details. This is usually in the form of documenting discussions and mutual agreement of details. PowerPoint is a common format for documentation. Figure 26 is an image taken during a technical workshop as part of industrialisation and build philosophy for future aircraft. Images are used to communicate technical information between engineers. This is a typical practice and is suited to aerospace where knowledge and experience are the primary source of design information. The future RASDM should be used as part of this design process and structure design in technical workshops.

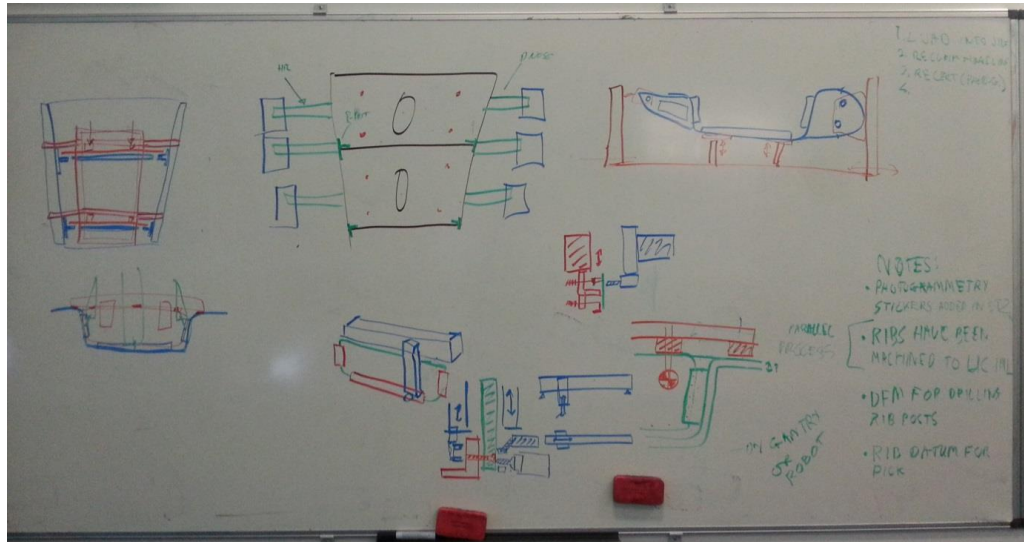


Figure 26. An example of a whiteboard exercise taken during a technical workshop as part of industrialisation of NGCW

2.2.2.5 Benchmarking

Airbus is global company with factories in Europe, USA and China employing over 70,000 people in total. Over 100,000 are employed in the UK through the extended supply chain. Often, solutions are devised in one location which are applicable to problems elsewhere in the company. What's more, innovations in other industries are often applicable to aerospace manufacturing. The long lifecycles of aircraft mean manufacturing and assembly isn't revised as often as industries such as automotive where new production lines are built roughly every three years. UK Manufacturing R&T use benchmarking for internal and external review to assess technical solutions and expertise. A benchmark brochure is used to back up conceptual claims or working principles of a similar solution that can be applied. Such documents identify existing suppliers and using proven technologies shortens development particularly for assembly where cost and time are sought to be minimised. Benchmarking documents are used for finding preferred solutions and suppliers when developing new system designs. They also serve to capture and build knowledge. An example slide for a reconfigurable tooling brochure is presented in Figure 27. The RASDM should capture and utilise this data.

Technology Benchmarking Brochure HiVol WP3.1.2.1 Jig Structure & Configuration	
WP3.1.2.1.2.3 Jig Configuration – <i>Rotational Jigs</i>	
	Description GEMCOR G86 Wing Fastening System The unique design, strength and flexibility of the GEMCOR G86 Five (5) axis CNC Positioning System has allowed it to be used in several wing fastening and wing related component fastening applications. "Frame in Frame" Work piece Handling or Simple Former Board wing panel supports are available depending on the required application. Furthermore, by taking advantage of the highly flexible and infinitely variable features of GEMCOR's All-Electric Riveters, several systems have been supplied with the capability to fasten both wing and fuselage panels on the same system
	Commission date
	ROM Cost
	Manufacturer Gemcor, Vought, Alenia
	Location
	Functionality
	Work piece to be machined / handled Wing , Fuselage assemblies
	Validated capability Existing Technology
	Status
Potential application to Airbus Notes	
© Airbus (Altkins) - TMDAWJ2B - Ref. PR0908922 - Issue 1 month 200X Page 20 	

Figure 27. Example slide of technology brochure review of reconfigurable tooling (Airbus UK 2009b)

2.2.2.6 Demonstrators

Aircraft development involves a great deal of testing and validation. Demonstrators are a fundamental part of the aircraft development process and are used to test and validate research (Carrera et al. 2004). A demonstrator is typically a partial-scale test rig for proving new technologies in an environment representative of production. Technological demonstrators build technical and scientific knowledge to de-risk projects and provide quantitative evidence for TRL gate reviews. Demonstration allows fast-tracking successful technologies, technical challenges can be revised and flawed concepts can be abandoned. Demonstrator programs make up for some of the experience of the designer. Demonstrators are often partial-scale depending on the novelty of the research. Timelines for demonstrators range from 6 months up to 5 years or more depending of the project requirements. Reducing the size allows Airbus to conduct feasibility tests at reduced costs prior to full-scale demonstration. This builds operational knowhow and confidence and highlights safety procedures. It is crucial that the findings from these demonstrators make their way into full scale production. The knowledge and lessons learnt should ideally transfer into full-scale production but is often difficult to translate into design because of the large volume of tacit knowledge. Figure 28 shows a test cell for production methods for the NGCW project. Knowledge from R&D work such as this has implications over future RAS design and so should be a consideration for a future RASDM.

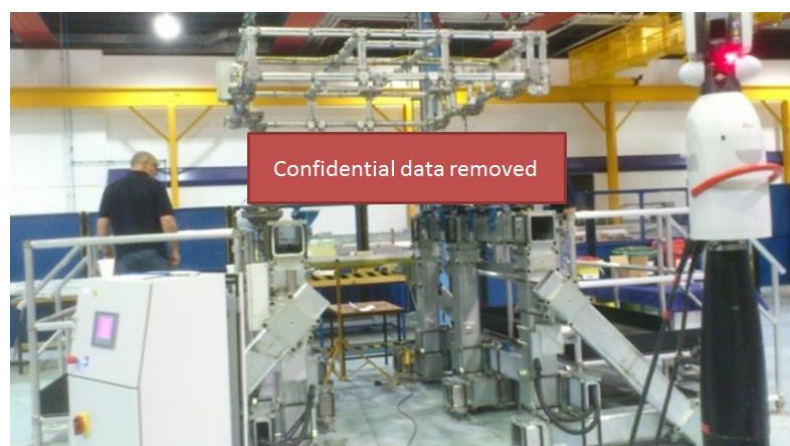


Figure 28. NGCW demonstrator cell (Airbus UK 2013)

Technical reports are written by engineers to document project findings. Reports range from brief summaries to detailed scientific studies over 20,000 words. Technical reports usually collate all the work of a programme and have accompanying documents such as presentations, test data, CAD, simulations, demonstrators or technology brochures. Reports are used extensively in Manufacturing R&T for in-depth studies. Technical report writers are usually technical lead on the project and have a wide body of knowledge on the subject and are referred to internally for expertise. They are often used for reference and as a source of design information.

2.2.2.7 Build Philosophies

The build philosophy is a key document used at Airbus to convey the ASD. It is usually a PowerPoint format document used in the design phase that illustrates how the wing is to be assembled. Typically, each major step of the assembly process is detailed with accompanying images to show the main working principles of the assembly process and equipment. The document is used by all stakeholders during technical workshops for developing the technical details of the design. Build philosophies are predominantly visual in nature to be communicable to stakeholders from all Airbus departments. The PowerPoint format enables easy updates and sharing in a collaborative environment. Build philosophies are developed by engineers using application of experience and tacit knowledge. As such some prior knowledge is assumed and not every detail is specified to communicate the design intent. Build philosophies are updated as the design is refined and technical details are specified. Generally, a build philosophy contains technical consideration of the assembly process, tooling, automation, tolerances, capabilities, RC and NRC and cycle time. These considerations have implications for operations, factory requirements, supply chain, procurement, finance and business. Also used by suppliers for quotations and tendering. These considerations inform risk management which directs future work and also highlight the main benefits. Build philosophies are a collaborative effort and require input from all stakeholders. Build philosophies have dramatic effect on the downstream phases and production. Up to 80% of the final aircraft cost is determined during this phase (Mas et al. 2012). Figure 29 shows an excerpt from a build philosophy which details the overall assembly process flow of a wing. Figure 30 shows a slide from the same build philosophy for top cover drilling. The process steps and cycle times are included along with CAD images of the cell to show working principles and to communicate the design to stakeholders for technical critique. A DM should be allow the designer to consider existing build philosophies and also produce a useable build philosophy for a RAS design.

2.2.2.8 Costing Methods

Cost is a crucial aspect of ASD and is estimated by suppliers and engineers to inform decision-making. Rough order-of-magnitude (ROM) costs are used at early stages to give an early indication and detailed cost models are used at later stages once the design is more detailed and costs can be estimated in real terms. Cost isn't always the main driver in early stages and focus is on technical feasibility and production advantages rather than cost. There is a general lack of costing techniques to forecast aerospace manufacturing development costs (Jones et al. 2014). Most cost estimations are based on previous experience and modelled in Excel software which is generally sufficient because of the high-value nature of aerospace. A detailed cost model has been developed to predict aerospace manufacturing technology development costs and man-hours (Jones et al. 2014). There are some efforts to integrate cost into the early stages of conceptual design (Curran et al. 2005; Gantois & Morris 2004). As such, existing costing methods should be compatible with the future RASDM.

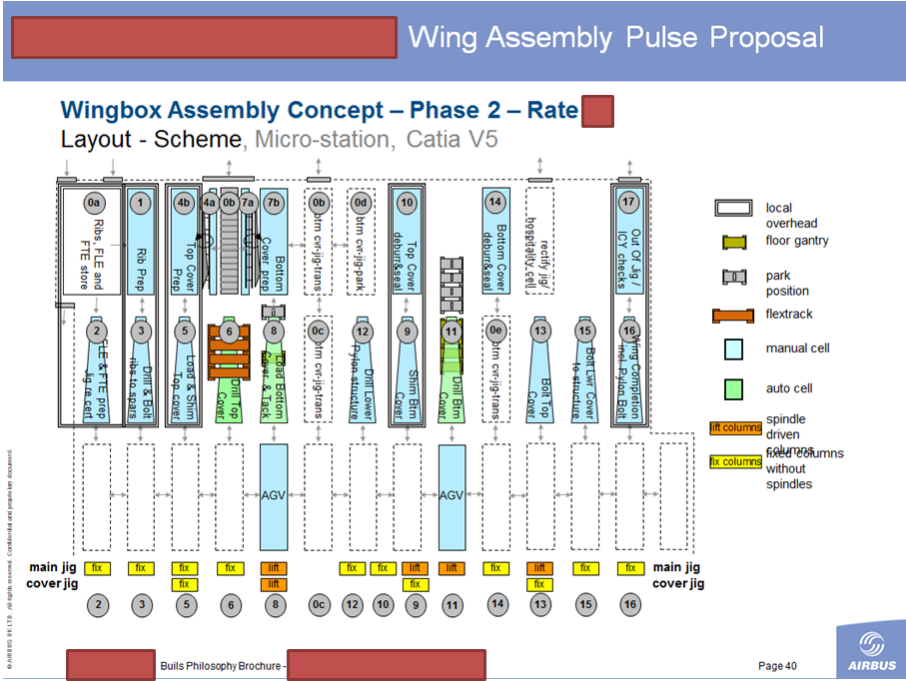


Figure 29. Example slide of a build philosophy used for a proposal for wing assembly showing system layout. Company and aircraft model data removed for confidentiality (T. Jefferson, University of Nottingham, et al. 2014)

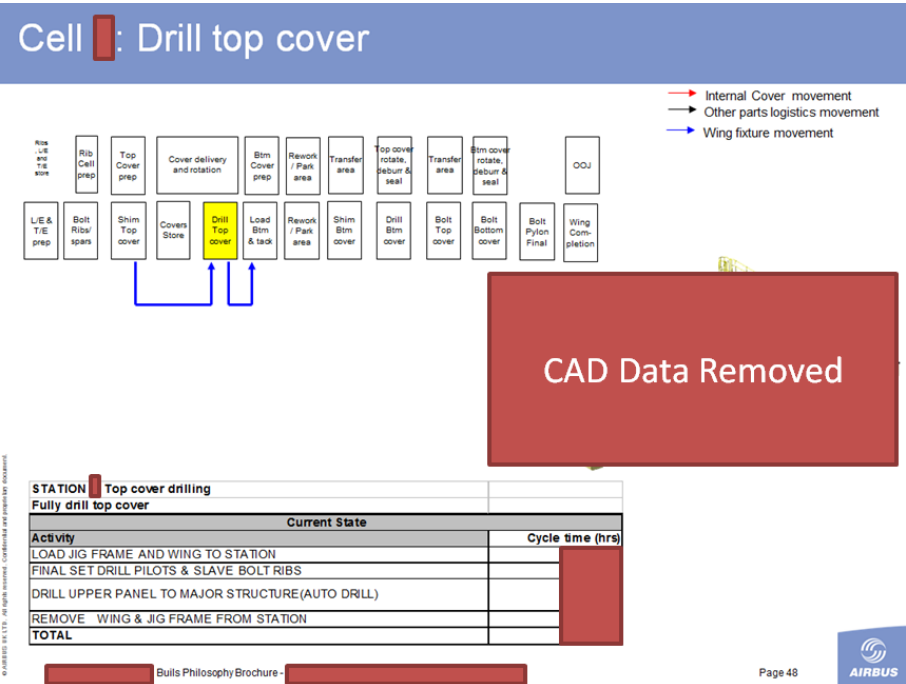


Figure 30. Example slide of build philosophy showing cell operations. Build philosophy shows CAD concept and cycle time data for cell. Build philosophy used for in-production aircraft (T. Jefferson, University of Nottingham, et al. 2014)

2.2.2.9 Airbus Design Issues

Key design issues were highlighted in discussions and lessons learnt technical workshops during the NGCW industrialisation project. Lessons learnt workshops for NGCW industrialisation found that requirements between future goals to research programs were not sufficiently traceable. One project was to investigate methods for high volume production but failed to demonstrate any scalability or cycle time data. The failure was

cited as both ill-formed requirements and a lack of requirements. A future RASDM should capture previous design issues for future reference and best practise.

2.2.2.9.1 Design Clashes

Knowledge capture sessions were conducted which found that some assembly subsystems were designed in isolation which lead to fixture and automation clashes. The tooling and automation required subsequent redesign which caused production delay and added cost. The cause was attributed to no analysis of design interaction during the project planning (T. Jefferson, University of Nottingham, et al. 2014; T. Jefferson, Woolley, et al. 2014)

2.2.2.9.2 Design Coupling

Some instances of coupling were discovered during the technical lessons learnt workshops. Coupling is where two or more parameters are linked by one source of adjustment. So setting the parameters is an adjustment loop that cannot always be resolved. The most significant example of this is shown in Figure 31. Two parameters were used to set three KCs on a wingbox section. The process of adjustment was unable to meet the KC tolerances because adjusting to set one KC resulted in moving the other KCs out of tolerance. The method was cited as being flawed and should not be carried forward for future work. Greater emphasis on the assembly system functions in the design phase could have helped avoid the use of a flawed concept.

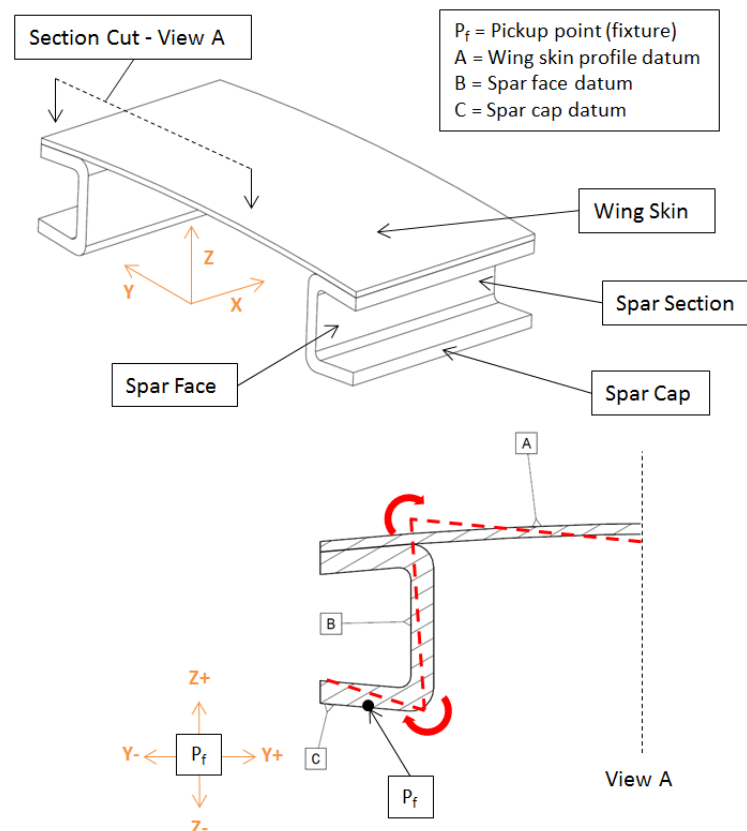


Figure 31. The spar caps were manipulated in Z and Y directions to reclaim the spar face datum. This primarily affects the hinge rib interface and thus the hinge line position and concentricity tolerances. Using the spar caps to manipulate the spar webs introduces moments about the corner radii which introduces stress and affects the spar face position and wing skin profile datum (indicated in red). The complexity of this method is due to coupling the system. 2 parameters (translation Z, Y) are used to set 3 requirements (Datum A, B, C) which means that 2 requirements are dependent on 1 parameter. Thus, changing one changes the other and results in an unresolvable feedback loop.

2.2.3 Summary and Design Method Limitations

Aircraft design is inherently difficult because of technical challenges and operational complexity. Inevitably, errors do occur despite best efforts and is part of the iterative

process and gate review. Assembly systems are developed in a knowledge-intensive, collaborative environment where the primary source of design is the engineers. The process is ad-hoc and heuristic in nature which is generally successful but leads to some problems and deficiencies. A TRL gate methodology is followed to systematically review the system design as the development progresses. Technical demonstrators showcase new technologies and are accompanied by technical reports which detail the findings. Build philosophies are the primary document for ASD and contain all the technical considerations. Two primary design issues were discovered during the knowledge capture sessions. First of which is requirements traceability where projects fail to deliver to customer needs. For R&T this represents wasted efforts and does not support production, implying a delayed program. Secondly, some technical solutions were found to have fundamental design flaws. Caused by either a coupled design or design clashes. Failure to deliver working solutions means repetition of effort which increases design cost and adds to delays. Coupled design required redesign effort at extra cost and wasted R&D resource. Tacit knowledge adds to the complexity of the design process where design input information is reliant on correct elicitation from engineers and relevant projects.

2.2.4 Implications for RAS Design

Airbus design methods have been reviewed and characterised. The implications for RAS design for an Airbus assembly system are summarised to inform the search for methods that are best suited to Airbus needs. The primary source of data for ASD is designer knowledge and the system design intent is conveyed in the Build Philosophy. A DM must maximise the use of designer knowledge. Previous work packages such as lessons learnt and R&D should be taken into account to avoid repetition and make use of insights which may be helpful to design. A method of systematic capture, review and formalisation of design requirements is needed. Additionally, this should improve the traceability of requirements to customer needs to avoid unsatisfied requirements. The selected methodology should integrate within Airbus structure and process which is the TRL gate method and collaborative design. Design inputs and outputs should be compatible with Airbus data. A resulting build philosophy should give technical consideration, noting capabilities and rates. Technical consideration must be given for moving from a static approach to changing structure. Reconfigurability will add complexity to an already complex process which is undesirable. A method of managing the design process in a systematic way should be used. Highlight design interactions will reduce the likelihood of design clashes and design coupling.

2.3 Future Aircraft Programs

Airbus UK have two major programmes which are at the ASD stage and require greater ramp-up. A program for future single-aisle aircraft is developing the next generation composite wing (NGCW). The project is in the early stages of development and there are small-scale assembly demonstrators which will inform the full-scale industrialisation. The other program is centred on dealing the backlog of the current single aisle program. Work is underway to move to a pulse line to mediate some of the backlog but RAS is under consideration for the long term. The requirements of the programs will also guide the search for a suitable methodology and will be used as case study applications for validation.

2.3.1 NGCW Industrialisation

The NGCW concept has been in development since the early 2000s and is anticipated to be in service circa 2025 (Figure 32). The NGCW is a novel integrated structure which is the first of its kind. Several small-scale demonstrators have been built to test various technologies and systems including some assembly processes. High volume production is expected for the aircraft and so ramp up and production rate are key drivers in the project, as is minimising NRC. Fixture methods are unsuitable for ramping up to the expected volumes whereas a reconfigurable assembly system has capability to change in structure without incurring prohibitive NRC. Figure 33 and Figure 34 present future targets. Environmental and performance targets are a significant step forward in technology compared to the current line of aircraft which means new wing technologies are required. Targets for higher rates and ramp-up are also stated. Assembly needs to be able to cope

with these new requirements to deliver competitive products. New technologies are under development and at varying TRLs. The design is not yet frozen as configuration options are not yet down-selected. The assembly system is also under development and so must use incomplete data and immature technologies in the design. Full-scale industrialisation of the assembly system is required from stakeholders to enable other workstreams to commence. In particular, supply chain setup, factory location, workforce and procurement. The existing R&D and knowledge must be factored into the ASD to produce a relevant assembly system. The ASD also needs to consider the parallel demonstrators (Figure 35) which influence the system layout such as systems installation.

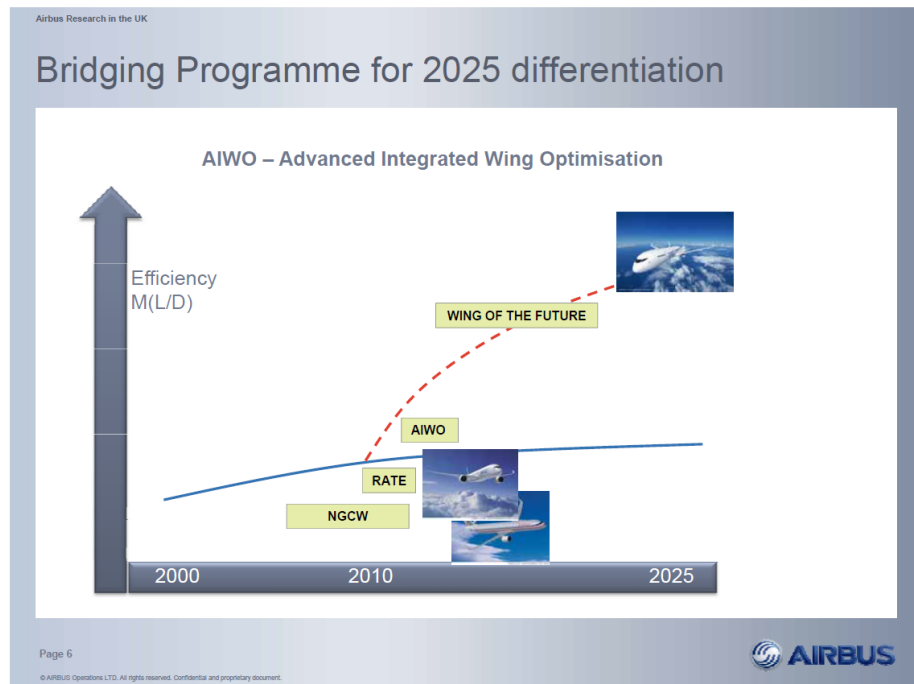


Figure 32. This thesis forms part of the manufacturing work for 'Wing of the Future' service entry in 2025 (Airbus UK 2012). Early work from the AIWO programme which forms the existing knowledge for Case Study One

Product Perspective		
Assessment of Targets		
Key Requirements	Current Best Practice	Gap
Low Cost	existing UCoS Gap	20+ % reduction
High Rate Manufacture	rate 32	50% increase
Rapid ramp up and Cut Over	rate 30 pyr after 2 years	10 fold improvement
Significant Performance Improvement	A350 standard	10% Weight Improvement
	A350 standard	3% Drag Improvement
Achieve early maturity	mature at EIS+	c.15 month reduction
DMC improvement	64 \$/FH	20% reduction
Reduced Operational Interruptions	99.4	Halve the no. of interrupts
Stringent Environmental targets	A350 standard	Noise reduction
		CFRP Recycling & Disposal
'Minimise' NRC	A350 standard	50% reduction in build cycle
		New 'Partnership' Development

Meeting these requirements will require new technical solutions & technologies (i.e a 'next generation' CFRP wing)

AIRBUS

Figure 33. Future aircraft targets compared with current capabilities (Dareck et al. 2011; Airbus UK 2012)

Baseline 2000	2010	2020	2050
Product Performance	Fuel Burn - 15% Maintenance - 15% Versatile Cabin Turn Around Time -30%	Fuel Burn - 50% No Unscheduled Maintenance Accident Rate - 80%	
Business Performance	Cost - 20% Time to Market - 20%	Cost - 40% Time to Market - 50%	Cost of Certification - 50%
Environmental Performance	CO ₂ - 15% NO _x - 20% Noise - No Increase from 20 Years Passenger Growth (Perceived)	CO ₂ - 50% NO _x - 80% Noise - 50% (Perceived)	CO ₂ - 75% NO _x - 90% Noise - 65% (Perceived) Emission Free Taxiing


**EVOLUTIONARY
TECHNOLOGY**


**BREAKTHROUGH
TECHNOLOGY**


**DISRUPTIVE
TECHNOLOGY**

Figure 34. Airbus performance targets for 2010, 2020 and 2050 (Dareck et al. 2011; Airbus UK 2012)

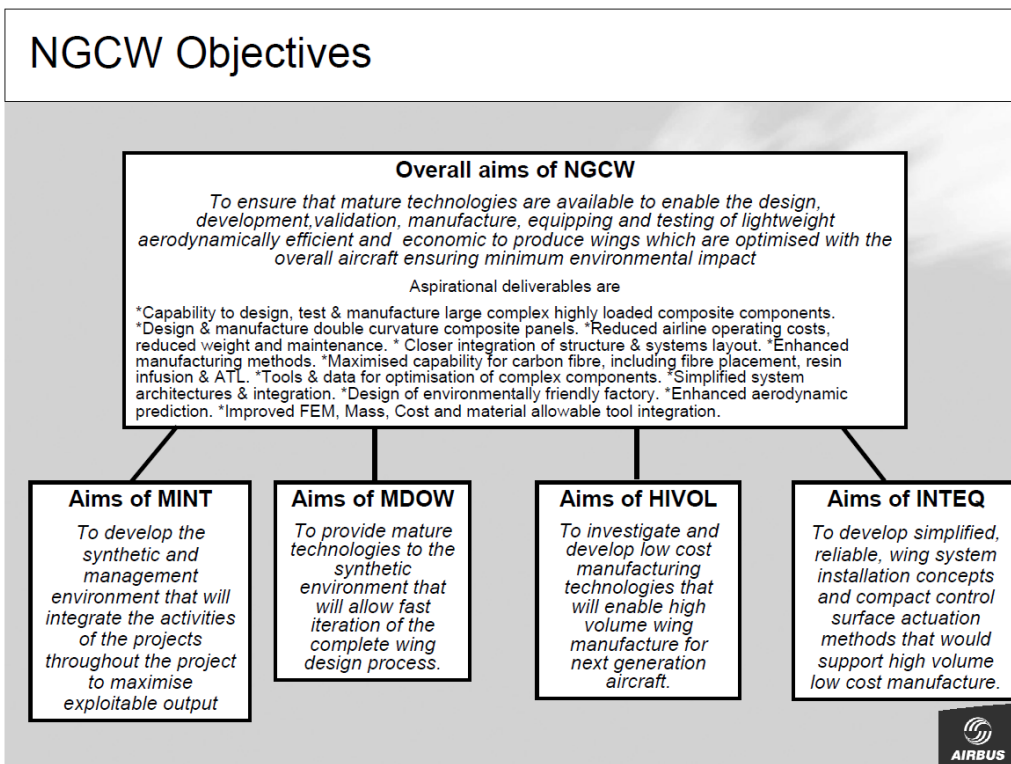


Figure 35. Aims and deliverables of NGCW split into four projects (Airbus UK 2007)

2.3.2 A320 Rate Increase

The A320 rate increase program aims to address the current backlog and the associated issues. Airbus plan to take the production rate from 42 to 60 by mid-2019 (Airbus S.A.S 2015a). The planned increase will use pulse line assembly over static fixtures with greater automation to reduce lead time (Flight Global 2015a). However, the new pulse line is only a short term measure to provide extra capacity. The build of the production line will take up to 4 years in which time the backlog is expected to expand from incoming orders. This is not capable of meeting the goals of ramp-up improvement because of lack of responsiveness to demand. Nor does the investment in tooling meet future requirements. A RAS designed for scalability is a potential solution to cost-effective ramp up and response to demand increase. An ASD is required to demonstrate how a RAS may function and compare for investment and operation against a conventional pulse line. The DM will be required to produce a 3D CAD of the assembly system and supporting build philosophy with tooling and assembly processes.

2.3.2.1 Implications for RAS design

The DM must be flexible for both future and current aircraft programs. Reconfigurable assembly has potential for the production of a future aircraft wing and to alleviate backlog of the current aircraft. It should be compatible with Airbus design data types and operate within the Airbus corporation. Outputs should also be in a format suitable for use by all Airbus stakeholders. The chief goals are ramp up and production rate which is primarily dealt with by scalability characteristics in terms of RAS. This should be specified from the outset in accordance with definitions provided by Koren (1999) within the constraints of Airbus protocols. Design should consider the wider aircraft programs and compliment parallel research projects to deliver to Airbus objectives. This will involve using incomplete data in regard to the ongoing NGCW project.

2.4 RAS as Potential Solution

Airbus assembly systems and design practices have been characterised and critiqued for the limitations and implications of a reconfigurable approach. This section explores the feasibility and practical challenges of designing a suitable RAS for wing structures. RAS are defined as such by being able to change structure to adjust capacity or functionality. These capabilities must be designed from the outset. Moving from static fixtures to a reconfigurable system has implications for design and feasibility because of the added complexity. Particularly with scalability, processes and equipment need greater independence to be able to be added or removed without extensive modification. This has significant implications for technical feasibility regarding accuracy and repeatability. Careful consideration of design for capacity and functionality is critical to a DM to fully embody a RAS.

2.4.1 RAS Design

RAS should embody a systems approach to design (Koren et al. 1999). Of the six characteristics, scalability and customisation are deemed to be essential to reconfiguring while the others are enablers (Koren & Shpitalni 2010). Scalability is of chief interest where Airbus are concerned to address the matter of ramp-up and production rate in light of the excessive backlog. Scalability depends on the ability to exploit functional and structural modularity within the system hierarchy (Lipson 2007). Therefore, a systems approach incorporating scalable and customisable characteristics should be a primary requirement of the DM. System architecture design must incorporate the ability to be changed easily and rapidly to adapt to changing environments (Fricke & Schulz 2005; Koren & Shpitalni 2010). For an RAS to change rapidly in structure, minimal coupling between structural units would allow the structure to change with minimal change to other processes i.e. greater independence of processes and equipment. Typically, this is an array of independent modules which are functionally uncoupled or loosely coupled which can be used interchangeably (Heilala & Voho 2001; Lohse et al. 2005). Indeed, such units can be deployed independently to increase production or change functionality incrementally. To provide customised flexibility over general flexibility, some method is needed to establish where the structural changes are required to change capacity and functionality i.e. specify the capacity needed where it is needed. What's more, to design such a structure in physical terms requires modelling of the coupling and dependence between structural elements. From which, systems can be specified according to the necessary requirements. Additionally, there are technical challenges implied by changing a structure which is a particular concern in aerospace. A review of enabling technologies is conducted to understand the technical feasibility of a RAS for wing structures to indicate the technological readiness of implementing a full-scale system.

2.4.2 Enabling Technologies

A RAS provides adjustable production resources by designing for rapid changes in capacity and functionality in areas specific to the product family (Koren & Shpitalni 2010). In the context of wing assembly this involves deploying equipment to reduce cycle time and modifying specific areas to accommodate different models. Thus, embodying the characteristics of scalability and customisation which are necessary for RAS.

2.4.2.1 RAS In Automotive

Due to mass customisation, increased commonality and short lifecycles in the car industry, RAS are more feasible and frequent. Nissan operate a notable example which illustrates the state of practice. Up to 8 types of vehicle are produced on a single line, whereas a conventional line can only produce 2 types of vehicles. The CapEx for a new model is reduced by 80% compared to a conventional line. The lead time for the tooling is approximately 3 months, whereas a conventional system needs approximately 1 year before launching. Subsequent NC systems have a Cp ratio (Process Capability Index) of 20-30% higher than that of a conventional system (Shimokawa et al. 2012). Figure 36 presents an example of reconfigurable tooling for automotive BIW where fixtures index into position using NC control. Previously, fixtures used rotary tables or slides to move different subfixtures to the assembly station. The automotive assembly is driven by mass demand for mass customisation where suppliers offer numerous models to satisfy a wide range of customer demands (Michalos et al. 2010). Assembly systems use these types of arrangements to produce all models on one production line. This has resulted in reconfigurability characteristics of customisation over scalability. The high levels of customisation in automotive are enabled by commonality in the product family. The automotive industry also uses product families extensively to reduce manufacturing costs and increase customer satisfaction by offering an extensive range of customisation options. A recent example is the Volkswagen Group MQB platform where the majority of components are shared across Skoda, Volkswagen, Audi and so forth (Buiga 2012). Common product architectures drastically reduces tooling costs and production time. The common platform means assembly processes are shared and so is much of the tooling. Corresponding RAS designed from the outset are capable of producing all models according to demand. Volkswagen Group are continuing to achieve cost savings on the order of 30 % and lead time reductions on the order of 50 % (Simpson et al. 2014).

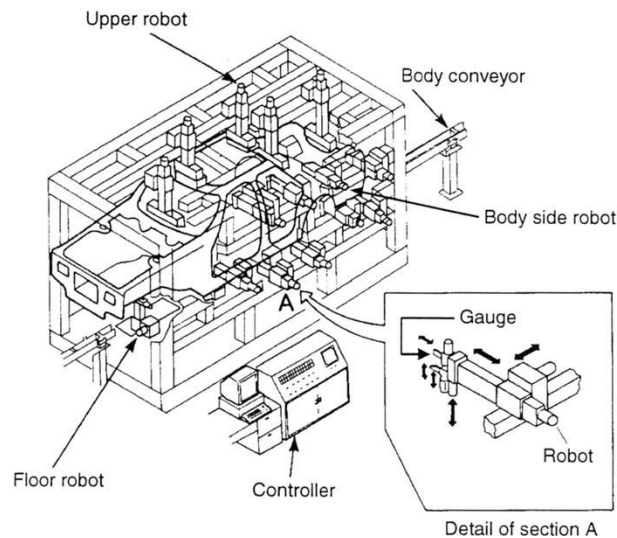


Figure 36. Nissan's Intelligent Body Assembly System. An example of reconfigurable tooling for automotive BIW (Shimokawa et al. 2012).

RAS are less prominent in aerospace assembly which is likely due to a number of factors. Legacy commercial aircraft produce less models in much lower volumes than automotive. Automotive produces new models roughly every three years which means automotive tooling has a very short lifecycle. Aircraft models are in production for 20 years or more and so the tooling is used for the life of the aircraft and the tooling design is duplicated to increase production rate. Conventional assembly of aerostructures is carried out using large, dedicated fixtures to hold the design tolerances. Assembly fixtures require extensive reinforcement to maintain the tolerances across a large area. Moving parts of the fixture as with a Reconfigurable fixture risk assemblies falling out of tolerance. Aerospace also have much longer lifecycles than automotive and so the demand for change occurs less frequently. Cost of flight certification is also a challenge particular to aerospace RAS. Wing structures have little commonality in terms of design and assembly processes despite

performing identical functions within the product family. This could be attributed to the launch dates of the aircraft programs which are more than ten years apart so designing for commonality was not feasible. Despite the maturity of RAS in automotive and the similarities in assembly, automotive solutions are not immediately applicable to aerospace under closer investigation. Reconfigurable solutions for automotive are centred around mass customisation which aerospace currently has little requirement for. Airbus do have aspirations for greater customisation capabilities of tooling but current goals are to focus on ramp-up and production rate in light of the current backlog of orders and future projections for greatly increased air travel. The scalability characteristic is what is most relevant to an Airbus RAS. This will involve changing some physical aspects of the assembly system to alter productivity. Airbus have historically always used fixed capacity structures which are then duplicated to increase production rate. Moving to a changing structure at Airbus is a significant departure in technical and operational terms where stakeholders have a typically conservative approach to production. What follows is a review of current practices in industry and academia to highlight existing systems or technologies which exhibit or can be adapted to embody the scalability characteristic.

2.4.2.2 Enabling Technologies: Capacity & Scalability

For an aerospace RAS to be adjustable in capacity, automation needs to be redeployed or duplicated to match production rate to demand. For example, automation for low rates needs to be deployed in multiple stations or repurposed for different operations. Conversely, to increase capacity, equipment needs to be added incrementally to reduce cycle time. This means large pieces of automation with multi-functionality need to be moved around the factory, repositioned and re-calibrated. This presents technical challenges over static tooling and automation but recent technological advances evidence this as achievable. Figure 37 presents an example of automation which is redeployed across several wing fixtures to perform drilling operations. The wing is for A400M which is produced by Airbus. A similar concept is presented in Figure 38 for Bombardier with the addition of bolting capability. A350 also uses a drilling system which is moved between fixtures to perform drilling operations.



Figure 37. Composite Automated Wing Drilling Equipment (CAWDE). The drilling system is moved between fixtures without reducing accuracy (Hempstead et al. 2006)



Figure 38. Wing assembly system with mobile automated drilling and bolting system (Electroimpact Inc. 2015; Krejci 2011)

Modern metrology systems can now be used to verify position or be physically integrated and adapt in real time. Recent reductions in setup complexity and costs mean metrology systems technologies congruent to RAS are now becoming viable for industrial use (Muelaner et al. 2013). Advances have been made in integrating metrology systems with conventional industrial robots. Recent robot technologies report increased positional accuracy feasible for airframe assembly (Devlieg 2010; Jeffries 2013). Robot systems are generally cheaper than bespoke design automation which means reconfigurability is becoming more cost-effective. Figure 39 presents a mobile robot platform which, with interchangeable end-effector tooling has the potential to be duplicated and added to assembly processes as demand increases to reduce cycle time. Reconfigurability is also enabled by technical advances in vision systems (Haldimann & Orf 2014). Despite technical advances in robotics and mobile automation for airframe assembly, systems are not applied to ramp-up production. This technology can potentially be applied in a systematic way by designing a system to be scalable from the outset, i.e. reconfigured to increase production.



Figure 39. Mobile robot platform for aerospace assembly (Adams 2014)

Airbus also have what is described as a 'flexible workforce'. Operators are generally multi-skilled and can carry out a range of assembly operations on different aircraft. Labour is strategically deployed when needed and provides some production rate flexibility. As fixtures are built, workforces are trained for immediate deployment once the fixture is commissioned.

2.4.2.3 Enabling Technologies: Functionality and Customisation

In addition to scalability, a system must also be customisable to produce part families. In an aerospace assembly application, tooling and automation needs to be changed for inclusion of rate-increasing automation during ramp-up as well as the specific differences between models. This means tooling and automation must either produce more than one type of geometry or be capable of rapid change in components for new variants. One example could include adding spindles to end-effectors to go from drilling single holes to drilling hole patterns. This could be designed to function on a mobile robot platform as presented in Figure 39.

Similarly, tooling pickups can be changed for different model geometries. New pickups can be designed to interface with existing locations to fixture new components. The tooling pickup systems themselves can also change geometry to produce model variants, this concept is presented in Figure 40 where Parallel Kinematic Machines constrain the primary structures. These technologies can be jointly applied with scalable technologies to have functionality and capacity needed when needed, i.e. evolve and adapt the production line for market changes. Notable examples include the demonstration of reconfigurable flexible tooling which uses a laser tracker for accurate assembly of wing subassemblies (Millar & Kihlman 2009). A similar principle is employed to position a robotic end-effector and hexapods (Kihlman & Engström 2002). This approach was adopted to assemble structures of the SAAB Neuron aircraft, presented in Figure 40 (Kihlman & Engström 2010). For more compliant parts, a reactive reconfigurable tool demonstrates the use of load cells to assemble fuselage panels (McKeown & Webb 2011). A flexible tooling fixture has also been demonstrated for assembling 17 different fuselage panels (Lum & Luo 2014).



Figure 40. Steward platforms are mounted to a modular structure to provide flexible fixturing for multiple geometries of a UAV. The tooling can be disassembled and reused elsewhere (Kihlman & Engström 2010)

Boeing are facing assembly challenges with the launch of the 777X to replace the aging 777. The 777X is a composite wing which is due in service in 2020 but the metallic 777 will stay in service for at least another five years as a freighter aircraft. Boeing plan to produce both variants on the same final assembly line at 8.3 aircraft per month (Flight Global 2015b). The line utilises mobile automation and does away with the large monolithic jigs that have traditionally been used. Boeing have developed a strong technical partnership with KUKA who are prominent in automation solutions in the automotive industry. KUKA have overseen the technical development and shared expertise with Boeing whose experience with robotics is minimal. There are significant differences between the two aircraft which have a gap between service entries of 26 years. The assembly system has been designed with enough customised flexibility to produce both variants without retooling. Boeing will maintain separate assembly lines for wings because of the lack of commonality between assembly methods. The 777X wing is composite and will use new robotic technology.



Figure 41. 777 automated fastening system using industrial robots and mobile platforms (Flight Global 2015b)

2.4.2.4 Summary

Some assembly systems technologies used for in-service aircraft demonstrate potential scalable and customisable characteristics but are not integrated into a reconfigurable system. Airbus and Boeing move automated equipment around the factory to perform different operations. Mobile robotic platforms are emerging as multifunctional assembly systems which are capable of achieving aerospace tolerances. Airbus also uses a flexible workforce in similar manner to enhance production when necessary. Systematic design from the outset could produce a RAS utilising these technologies that offers improved ramp up and production rate.

2.5 RAS Design Methodology Requirements

A RAS for wing structure assembly is technically feasible since there are existing assembly systems for in-service aircraft which demonstrate scalable and customisable characteristics, which are necessary for reconfigurability. While characteristics are demonstrable for reconfigurability, they are not integrated in such a way to provide rapid change in capacity and functionality. The development of a methodology will provide the necessary design steps to specify a reconfigurable ASD that provides exactly the capacity needed when needed. An explicit methodology is needed to formulate a RAS design in the complex Airbus design environment. A systematised process should deal with the added complexity of changing structures and highlight interactions and dependencies in the architecture to meet assembly system requirements. A structured framework will allow operation within the boundaries of Airbus design practices, taking into account knowledge intensive design process, iterative nature of design using existing research and data combined with customer demands and innovation. The methodology should also consider the limitations of current assembly systems and design practices along with future aircraft

requirements. These elements are considered and used to derive a set of requirements to guide a literature search for a DM. A set of requirements derived from a review of Airbus needs and limitations for transition to RAS ensures that a suitable DM is selected. Guiding requirements also narrows the search and avoids unsuitable methodologies. The DM requirements are stated in Table 5 followed by supporting rationale of each requirement.

Table 5. RAS Design Methodology Requirements

Requirement No.	Requirement specification
<i>The methodology should allow the designer to:</i>	
Requirement 1:	Specify scalable and customisable capabilities in the design for cost-effective ramp up and model change requirements
Requirement 2:	Identify functional and physical dependencies in the assembly system design
Requirement 3:	Identify system interactions in the design phase
Requirement 4:	Analyse impacts of change throughout the lifecycle of the factory
Requirement 5:	Employ the use of designer knowledge and experience
Requirement 6:	Systematise and structure the design process
Requirement 7:	Generate 3D concepts (working principles) early in the design phase to aid decision-making
Requirement 8:	Synthesise customer needs with existing Airbus data and translate into physical designs
Requirement 9:	Compatible Airbus protocols and documentation

2.5.1.1 Scalable and Customisable From the Outset

RAS should be designed from the outset to be scalable and customisable (Koren & Shpitalni 2010). The methodology must be able to specify or identify these in the design to embody the necessary characteristics for reconfigurability. Scalability in particular is crucial to an Airbus RAS to address the problems of ramp-up which is the main driver of the project. Scalability should be specified in cost-effective manner so as to have targeted flexibility as opposed to general flexibility which incurs unnecessary cost. The chosen method should be able to specify to a reasonable level of detail to progress to physical detailed design to ensure a system design is technically feasible and has workable functions to change in structure.

2.5.1.2 System Independence

For a system to be changeable in structure the effected elements need to be modified independently or affecting the minimum number of elements. That is to say, reconfigurability is enabled by physical and functional independence. Independence needs to be specified or visualised through the design from conceptual level to detail level so independence can be specified where it is needed for scalability and customisation. Highlighting dependencies in the system architecture enables design for modularity and therefore reconfigurability.

2.5.1.3 Highlight System Interactions

Moving from a static system to a reconfigurable system where the structure changes means an increase in the number of interactions between system elements which increases design complexity. Incremental increase in capacity by adding equipment is likely to have various impacts on the wing, assembly process or surrounding equipment. Highlighting system interactions supports reconfiguration planning and testing and system independence. Identifying system interactions in the design phase informs subsequent detailed design of equipment and processes which should be consistent with higher level specifications for independence.

2.5.1.4 Plan and Test Reconfigurations

A RAS should be able to rapidly respond to changes in demand. The designer needs a means to assess impacts of change throughout the lifecycle of the factory to plan reconfigurations; both for planned and unplanned changes. A method to model the assembly as a system is required to show how changes to one area impact the other parts of the system. This assessment informs the various stakeholders of the necessary modifications and the system output after reconfiguration. This is important in decision-making where capital investment is needed. An added benefit of such a model is to understand the level of reconfigurability of the design which can be assessed before production. Designers can understand the impact of various scenarios which is useful for strategic planning and also partially validates the reconfiguration capability of the system design.

2.5.1.5 Designer Knowledge and Experience

Current solutions and decisions are produced by the engineering team based on collective knowledge and experience. Any methodology should promote the use of designer knowledge and experience in an effective way. Design is a knowledge-intensive activity relying significantly on the experience of engineers in multiple disciplines during the manufacturing systems design process (Efthymiou et al. 2015). In order to meet the technical challenges set for the next future of aviation, new design systems are required to increase engineers' productivity and better exploit designers' skills and creativity. (La Rocca & Van Tooren 2007). Increasing the available knowledge and making it more readily available may reduce process overheads and ensure better use of key people (Harvey & Holdsworth 2005). RAS is likely to increase design complexity with the added requirements for scalability and customisation. A formal methodology should enable engineers to draw from personal experience and knowledge with respect to customer requirements and technical constraints. This should cover conceptual design and detail design. Assembly system designers use a mixture of existing solutions and innovation. The methodology should allow systematic consideration of certified and uncertified solutions using relevant information to make informed decisions.

2.5.1.6 Provide Structure to the System Design Data

ASD is a complex process of formulating a functional arrangement of processes and equipment to satisfy a set of interrelated requirements. Airbus design takes place in knowledge-intensive, collaborative environment and so generates vast amounts of data because of iterations between stakeholders (Mas et al. 2014). It is important that this data is consistent and traceable to ensure the safe operation of the aircraft. Adding reconfigurability increases the design complexity. A DM for RAS design should provide structure to the system design data so it is manageable, consistent and traceable. The designer should be able to manage the complexity without detriment to utilisation of knowledge. Design is the synthesis of existing data (tacit and explicit) and creation of new data (ideas and solutions). The current design approach is ad-hoc and so is time inefficient (La Rocca & Van Tooren 2007). A methodology should offer a systematic and orderly process to structure the design data and guide the designers. Carefully managing the design data improves communication by minimising the amount of iterations by allowing the designers to focus on separate manageable sections of the design independently whilst remaining consistent with the system functions.

2.5.1.7 Generate Concepts Early in Design Phase

Aircraft design and industrialisation is an iterative process. An early system view of processes, equipment and technologies is important for decision-making between stakeholders to shorten time to market as much as possible. A methodology which generates 3D concepts (working principles) early in the design phase will aid decision-making. A build philosophy is a central document to ASD and initialises other work packages. The early creation of a build philosophy enables early communication between stakeholders and drives development. Particularly for future aircraft where the design is not yet frozen, the build philosophy can influence aircraft design. Because of the ramp-up issues found by Airbus in recent times, assembly has stronger influence on aircraft design.

2.5.1.8 Translate Customer Needs and Airbus Data into Physical Designs

Assembly systems require design input from various sources. Knowledge-based information, customer requirements, lessons learnt, R&D work and certification all exert some influence over the ASD. The designer must gather and synthesise all this information to create a formally agreed set of assembly system requirements and a corresponding physical system design. A RASDM should be constructed in such a way to enable or enhance this process, either by approach or framework. Particular consideration should be given to incorporating R&D and lessons learnt, translating requirements into physical designs, using incomplete data and facilitating knowledge reuse and innovation. Aircraft development is a long and iterative process and aerospace spend vast sums of capital on research and development of new technologies and systems, both for aircraft products and production methods. This knowledge and information should be utilised when designing an assembly system to exploit existing investment and avoid unnecessary repetition. Equally, knowledge of the current system is useful in designing a future system; known as lessons learnt. A RASDM should seek to maximise the use of R&D and lessons learnt data as well as the associated knowledge acquired. ASD involves multiple stakeholders in various engineering disciplines as well as the requirements of aircraft operators. These customer requirements are often contradictory and conflicting and a compromise is needed. Some requirements are strategic such as using a certain technology or supplier, sometimes they are even anecdotal, such is the nature of knowledge-based development. Often there are ideas, aspirations and concepts which are from non-technical sources. Certainly in the early design phase, aircraft design data is incomplete and industrialisation needs to agree on assumptions to progress industrial design. The designer needs to work through these and assess which ones are requirements for the design. A DM should aid the designer in synthesising customer needs and aspirations and translate into physical designs which should be traceable from customer requirements and concepts to detail design. Aircraft design can be described as an ongoing process of development. Designers often reuse processes to minimise certification costs but this often ignores innovative technologies which could offer long term benefits. The DM should allow the designer to consider reuse of processes but remain open to innovations where appropriate.

2.5.1.9 Business Compatibility

Reconfigurable assembly represents a novel departure from standard assembly practices at Airbus. The DM should communicate a build philosophy along with supporting documentation in conventional Airbus format which is interpretable by all stakeholders. Equally, a DM will be applied to Airbus ASD projects so should use Airbus data and documentation.

2.6 Summary

Chapter 2 presents the current state of practice for assembly systems and ASD at Airbus. The limitations of which, were highlighted as large monolithic structures of fixed capacity which have slow response to ramp-up and model change. Increasing production rates involves adding fixtures or production lines which has led to a substantial backlog. Then, design practices were reviewed to understand typical data types for transition to RAS design. Thus satisfying research objectives 1-3 stated in Section 1.10.1. The feasibility of implementing RAS was discussed and noted new enabling technologies make RAS possible for wing assembly. The current state of assembly and design practices was used to create requirements for an Airbus RAS DM, which delivers objective 4. The DM requirements will guide literature search for appropriate design methodologies.

Chapter 3 Literature Review

Airbus requirements for a RASDM were formulated in Chapter 2 by a review of the current assembly system and design practices. Chapter 3 compares these requirements against current academic literature to identify and compare existing methodologies suitable for RAS design, which is Objective 5. The review begins with searches for complete methodologies followed by searches for individual tools and methods then onto perspectives and concepts. Studies are compared with the DM requirements to highlight methods appropriate for application to Airbus RAS design. Rationale of the search process and critique of the research in relation to requirements is provided. The literature review finds design methodologies only partially satisfy the DM requirements. Critical analysis finds knowledge gaps where work into RAS design has shortcomings for industrial implementation and ramp-up. Most work is centred on automotive issues for mass customisation and variety. Aerospace RAS is much less detailed but several investigations go some way to satisfy individual requirements. Modifying an existing methodology to include extra methods and tools suited to Airbus is proposed to address knowledge gaps in the research and satisfy Airbus requirements for a DM.

3.1 RAS Current State-of-the-Art

Section 2.4.2 presented examples of current equipment in use for in-service aircraft which could feasibly be adapted to embody RAS characteristics by careful system design for appropriate functions for scalability. What's more, RAS have been used successfully in the automotive sector for a number of years. Despite this, there are no full-scale examples of RAS for aerostructures. This section substantiates this claim further with critique of ongoing research of RAS technologies, in addition to the industrial review. Possible explanations are offered for the lack of RAS in aerospace.

3.1.1 Current Trends in RAS

In 1999, RMS were introduced as a new class of manufacturing system (Koren et al. 1999). New research streams quickly developed to bring about future production (Mehrabi et al. 2000; M. G. Mehrabi et al. 2000; Mehrabi et al. 2002). RAS research followed as a subset of RMS using the same principles (Swanson 1999; Ratchev & Hirani 2001; Arai et al. 2002; Yu et al. 2003; Setchi & Lagos 2004). Since then, research has been carried out to advance reconfigurable techniques and supporting enablers. Much progress has been made in regard to equipment, software and control, optimisation techniques and economics (Dashchenko 2006; ElMaraghy 2008). However, little progress has been published on deploying these technologies through design methodologies. Some recent efforts have focused on concurrent development of product families with RAS (Galan et al. 2007; Bryan et al. 2013; Kashkoush & ElMaraghy 2014; Ashraf & Hasan 2015). This concept is used successfully in automotive assembly systems for mass customisation and model variations (Simpson et al. 2006; Simpson et al. 2014). This has led to the automotive RAS. It is hoped that this trend can now extend to aerospace assembly.

Advances continue to be made in the technical aspects of RAS, particularly robotics, fixturing and control. Optimisation of system planning and resourcing also continues to be a developing trend (Travaini et al. 2002; Lohse et al. 2005; Gyulai et al. 2014). Advances in robotics continue to improve positional accuracy and cooperation. Systems are able to demonstrate self-awareness through sensor and software development and can adapt to changing manufacturing environment (Bolmsjo 2014; ElMaraghy & ElMaraghy 2016). Mobility functions have also been demonstrated which means robots can reposition elsewhere on the production line to enable convertibility (Michalos et al. 2014). Reconfigurable fixtures have reached production maturity and are in place in many automotive assembly systems (Michalos et al. 2010; Simpson et al. 2014). Recent research has included force feedback and positioning algorithms to compensate for variations caused by both fixture manufacturing and the assembly process itself (Jayaweera et al. 2015; Zhang et al. 2016; Olabanji et al. 2016). PKMs feature prominently in RAS research and are a key enabling technology. The latest work conceptualises a new class of PKM machines which uses a novel locking-joint design to provide translational as well as

rotational movements (Carbonari et al. 2014). This could offer greater range of movement and positions for reconfiguring fixtures for model changes. For long-term prospects, RAS researchers are looking to utilise cloud-based and evolvable or holonic systems using artificial intelligence (Chaplin et al. 2015; Wu et al. 2015; Kruger & Basson 2016).

Persistent RAS research is diverse and continues to make technical advancements since its inception. Innovation continues to offer improvements to productivity and market responsiveness. Though despite these advances, there is a lack of industrial implementation for full-scale *systems*. That is, physical demonstration of groups of assembly cells being able to change in structure to change, particularly for capacity. In particular, there is a lack of reconfigurable systems implemented for joining large subassemblies. Albeit with the exception of automotive which uses reconfigurable fixturing for mass customisation and assembling multiple models. RAS research for automotive and aerospace sectors are reviewed in more detail for specific challenges for capacity change and possible application of automotive techniques to aerospace.

3.1.2 Automotive State-of-the-Art

Automotive assembly systems such as the ones presented by Michalos *et al* (*op. cit.*) are considered reconfigurable because of demonstrated customisation and convertibility. Automotive assembly state-of-the-art is reviewed for technical applicability to aerospace because of full-scale RAS implementations of comparable magnitude to aircraft assembly. Despite some radical differences, automotive and aerospace are similar and share interdependency of the same suppliers and equipment plus mutual sharing of new technologies and methods (Phillips 1999; Bajpai et al. 2014). Recently, the automotive industry has been driven by customer demand for personalised vehicles rather than a standard product. Vehicles are now extensively customisable where the customer acts as co-designer in the purchasing stage (Alford et al. 2000; Tseng & Hu 2014). This is made possible by modular vehicle architecture where different combinations of subassemblies create different models (Simpson et al. 2006; Paralikas et al. 2011; Simpson et al. 2014). This has forced assembly systems to adopt greater flexibility for multi-model production where previously each model would require a separate assembly line. Assembly systems are becoming more complex and flexible tooling is being introduced to provide this customisation capability (Hu et al. 2008; Michalos et al. 2010). This type of customisable and convertible RAS has been introduced for rapid change in model using one production line. An example of which is presented in Figure 42. Each cell reconfigures to new models according to customer demand. Cells can reconfigure individually for changes to specific areas of the chassis. In principle, this changeover of tooling can be applied to aerospace assembly ramp-up, given careful design. Where new pieces of automation are added to reduce cycle time.

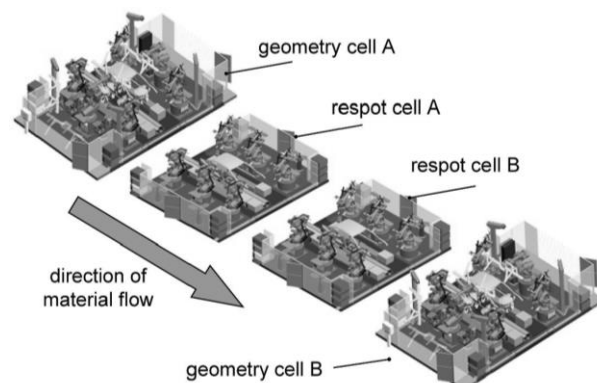


Figure 42. RAS which has customised tooling to reconfigure to different model variants (Soetebier et al. 2011)

Figure 43 presents an example cell which uses customised tooling which automatically repositions for new geometries. This has resulted in overall reduced tooling costs by elimination of extra production lines. With high volumes of vehicle production, changeover time of these reconfigurable cells is critical to production rate and has driven much of the technical development for automotive RAS (Soetebier et al. 2011; Shimokawa et al. 2012).

This RAS is implemented as full system and in-production today. The modular product platforms increase commonality between models which reduces amount of unique tooling and standardises the tooling design. This shortens time-to-market and reduces the length of the design phase.



Figure 43. Reconfigurable cell for BiW assembly. Underbody tooling (centre) reconfigures for different models. Bodyside tooling (left and right) reconfigures for different variants to suit each model (Soetebier et al. 2011)

Because of the high volumes and time-to-market priority, automotive RAS are generally not focused on ramp-up from low volumes as seen with aerospace. Automotive research into ramp-up addresses product launch with high-volume production (Staeblein & Aoki 2015). The high volumes and high frequency mean automotive systems have to be designed for high-volume and mass customisations from the outset (Colledani et al. 2016). This is reflected in RAS design methodologies which have been developed to manage the added complexities of design and operation (Modrak et al. 2015). Methodologies guide design for customised tooling and manage the variety. Figure 44 presents an example methodology where chassis components correspond to elements in a matrix which in turn correspond to tooling for vehicle underbodies (Al-Zaher & ElMaraghy 2014).

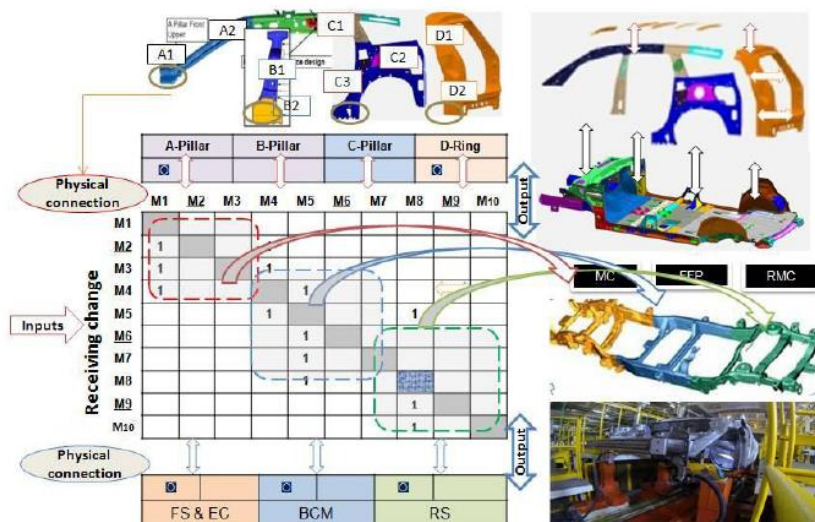


Figure 44. DSMs are used to map model changes to reconfigure the assembly system (Al-Zaher & ElMaraghy 2014)

Changes to body can be represented in changes to matrix elements which is mapped to tooling which is then reconfigured for a new model (Figure 45). This methodology has also been used to implement RAS for BiW (Al-Zaher et al. 2013). Alternative methodologies are oriented to the same goal of mass customisation with similar approaches. Such as, application of artificial intelligence and Multi-Criteria Decision-Making (MCDM) methods to evaluate configurations (Mourtzis et al. 2015). Another model demonstrates automatic redesign of assembly systems based on product commonality (AlGeddawy & ElMaraghy

2013). These methodologies are suited to mass-customisation problems and lack major consideration of enabling ramp-up in terms of technical implementation and operation. Most likely due to requirements specific to the demands of automotive production. These methodologies could be readily adapted to model aerospace assembly system DSMs and map interactions and changes. Ramp-up change could be modelled by adding matrix elements and highlighting the affected elements for reconfiguration.

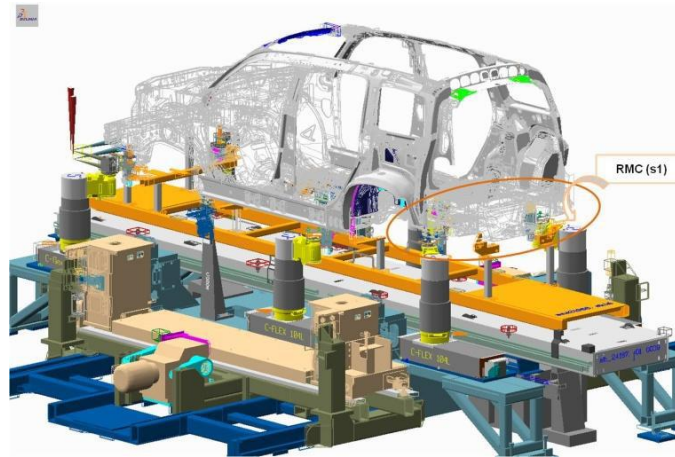


Figure 45. Reconfigurable assembly tooling for mixed BiW models (Al-Zaher & ElMaraghy 2014)

3.1.3 Aerospace State-of-the-Art

In contrast to the automotive sector, the aerospace industry is not subject to mass customisation demands. At Airbus, ramp-up and production rate have become the limiting factors for assembly systems, discussed in 2.1. Existing systems have not been able to match the increases in demand and new assembly systems call for greater ramp-up and total capacity. Currently there are no published references of full-scale RAS implemented for aerostructure assembly, unlike automotive. Though, there are advances to RAS-enabling technologies developed on individual programs. Aerospace RAS research is discussed to establish the current state-of-the-art.

Advances in mobile robotics were mentioned in Section 2.4.2.2 where mobile robot systems are being used to assemble in-service aircraft. A shift in research towards this principle is also evident in academia (Michalos et al. 2014; Bourne et al. 2015). Mobility is cited as a key enabler to the scalability aspect of reconfigurability where equipment does not have a fixed position and can be repurposed (ElMaraghy & Wiendahl 2009; Rösiö & Säfsten 2013). The use of robots in aerospace is enabled by the additions of metrology and control technologies (Jamshidi et al. 2010). This has enabled assembly of large structures and robot cooperation (Makris et al. 2012; Maropoulos et al. 2014). This suggests that redeployment of automation could be utilised for reconfiguration purposes. The design methodology should enable the designers in doing this to the right level of scalability.

Reconfigurable fixtures are also being developed for large structures, several of which have been demonstrated in lab environments. Live fixturing has been developed to adapt to maintain KCs despite deviations during assembly (Martin et al. 2011). Flexible tooling (Figure 46) has also been demonstrated for rib assembly where one system can change geometry for multiple components positioning (Erdem et al. 2016). A similar system is demonstrates fixturing of a secondary wing structure which uses adaptive fixture joints (Zhang et al. 2016). Reconfigurability has also been considered for handling large components which enables automated customisation for primary structures (Müller et al. 2013). Equal to deploying reconfigurable automation, reconfigurable fixtures should be specified in the design methodology to the appropriate levels of customisation.

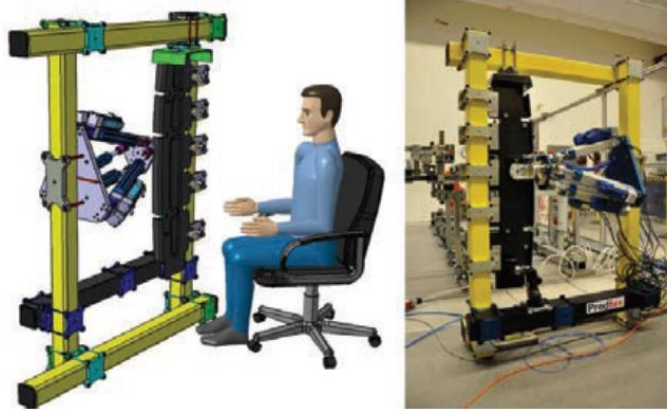


Figure 46. Reconfigurable tooling demonstrator for aerostructure assembly (Erdem et al. 2016)

Aerospace RAS technologies is an ongoing area of research. Technologies are available and show characteristics suited for RAS but are not implemented in full systems and bear no mention of rate, ramp up or scalability. Relevant RAS design methodologies mostly apply to automotive or specific tools such as fixtures with few practical implementations (Al-Habaibeh et al. 2003; Krebs et al. 2013; Xiong et al. 2013).

3.1.4 Critical Analysis

State-of-the-art reviews have been conducted for automotive and aerospace assembly to call attention to limitations of current knowledge for aerospace RAS. As well as identification of potentially adoptable RAS practices in the automotive sector where reconfigurability has advanced to production. Production RAS have been implemented for automotive assemblies to enable mass customisation and model change. Reconfigurations for different models embodies customisation and convertibility characteristics. RAS aerospace research is ongoing and mostly based in lab environments but has demonstrable reconfigurability characteristics for scalability using mobile robots and customisation through flexible fixturing. No full-scale RAS in aerospace is apparent despite supporting technologies with production capabilities. Nor is there detailed discussion of ramp-up or rate for aerospace in this regard. There are several RAS design methodologies for automotive which address customisation but not scalability but no aerospace RAS design methodologies were found. The possible reasons for this are discussed in relation to developing a new RASDM.

Firstly, the calls for greater flexibility are relatively new due to recent increases in demand and future forecasts. Approaching the ramp-up issue from a tooling and assembly point of view is new to Airbus Manufacturing R&T where priorities were previously given to developing low-TRL technologies or focus on issues specific to particular assembly processes on jig. Secondly, Airbus produce aircraft in much smaller volumes compared to automotive so there may be a lack of expertise for high-rate assembly. Airbus have a total of 8926 aircraft in operation which includes aircraft designed in the 1960s and 1970s such as the A300. By contrast, Toyota Motor Corporation produced over 10 Million vehicles in 2013 and in the same year Airbus delivered 626 aircraft (Toyota Motor Corporation 2014; Airbus S.A.S 2016a). Thirdly, some technological developments are relatively new, particularly mobile robotics and so opportunity to demonstrate full-scale is yet to occur. Issues of cost and scale may also restrict demonstration at production level. Additionally, aerospace have longer lifecycles so there are naturally fewer opportunities to design new production systems. Current production systems use dated technology and methods which may also highlight lack of expertise. Aerospace is also under greater restrictions due to certification and cost thereof. System design efforts may be conservative in terms of innovation because of this. It is also clear from automotive examples that modular architecture and greater commonality enables reconfigurable assembly and reduces some of the complexity for design and operation. The reasons stated offer potential explanations for a lack of RAS design methodologies suited to aerospace. A deeper search is now carried out to see if this can be corroborated with other researchers.

3.2 Cited Lack of Design Methodologies

A lack of design methodologies for reconfigurable systems are cited by other researchers which validates the findings of the previous section. Research is reviewed beginning with the earliest publications. Early research by Mehrabi *et al* (2000) consider RMS design in detail in '*Reconfigurable Manufacturing Systems: Key to future manufacturing*'. RMS design is stated to include architecture design, configuration design and control design. It goes on to state that system architecture is critical for the system to function as expected but existing methodologies for architecture design do not consider reconfigurability and convertibility performance. Further still, little work exists for system requirements for optimal architecture design. Researchers clarify that for a system to be reconfigurable, subsystems and their components must be designed to be so from the outset, using scientific knowledge, in order to possess reconfigurable characteristics. Design of reconfigurable systems is accomplished through a systematic approach, supported by software tools that relate the product features to modules of processing units and yield a system layout and process plan. Indeed, a key research issue in system level design should be the development of a systematic approach for design of RMS at the system level. Inadequacies were found in concurrent design methods for modular systems not capable of dealing with the complexity and scalability of RMS which have a large number of variables. In addition to a lack of available tools and methodologies and lack of communication between product design and manufacturing design. Consequently, researchers describe a potential approach to developing a systematic DM could be to adapt existing non-reconfigurable design methodologies by extending for consideration of time and changes. Another relevant point raised concerns transitioning from non-reconfigurable to reconfigurable in industry. The work concludes new theories, design concepts, and methodologies should be developed to design the systems and evaluate various configurations including development of a unified approach for design and construction (Mehrabi et al. 2000). An investigation by Setchi & Lago (2004) restates the need for reconfigurable manufacturing citing roadmap studies commissioned by American and European research councils. Again, calling for design methodologies to be developed for system level architecture design, hardware design and software design and also including considerations of cost-effectiveness. A technical review of reconfigurable fixtures, robotics and handling systems research establishes technologies are available for application. Additional research issues cited include modularity, business modelling and training (Setchi & Lagos 2004).

Bi *et al* (2007) focus specifically on the current state-of-the-art of RAS. The work identifies both academic and practical issues and highlights future research directions. There is detailed discussion of industrial needs for improved productivity and responsiveness and the suitability of RAS as a justified solution. Research into enabling technologies is reviewed, namely: DfA, system modularisation (enable scalability), modular robotics, flexible fixturing, fixtureless assembly and flexible handling. Few practical systems available to demonstrate RAS are reported. Difficulties in developing RAS is discussed which cites methodologies and tools to support design. Also, separation from product design and premature technologies. Further effort is needed for quantifying reconfigurable requirements and modelling RAS designs (Bi et al. 2007).

Further work by Bi *et al* (2008) takes a broader view of the state-of-the-art for RMS. Design is cited as a critical issue once more and considers specific design issues, including system ramp-up and system architecture design. The work finds that prototypes to date are machine level have been designed intuitively and '*a systematic design methodology is still lacking*' (Bi et al. 2008). Another relevant point is raised: when designing reconfigurable production systems, the complexity level gets even higher since reconfigurability must be considered from the start throughout the entire process. Lack of design methodologies is addressed directly by Koren & Shpitalni (2010) which cites a lack of design procedures for RMS including RAS, a mathematical design method is proposed with a machining example. The work concludes that systematic design methodologies are suited to systems with large capital investment and may help minimise cost.

The most recent work investigates theoretical and practical challenges of implementing reconfigurable production systems. Rösiö & Säfsen (2013) review production system design methodologies and finds that they do not consider reconfigurability to a large extent, as well as a general lack of industrial implementations. They also find RMS literature lacking in describing how to include reconfigurability in the design process. Four case studies were carried out on the consideration of reconfigurability in the design process for four projects at two different companies developing assembly systems. The researchers concluded a lack of guidance on how to include the idea of reconfigurability in the production system design process. In addition, a holistic view is required for design because of the multi-disciplinary nature of ASD. Three needs are identified from the work to implement industry RAS which are as follows: (1) to use a structured design methodology; (2) to gain knowledge of reconfigurability and its characteristics; and (3) to include the reconfigurability knowledge in a structured DM.

3.2.1 Summary

Since the inception of the RMS paradigm, researchers have sought new innovations to bring reconfigurability to implementation. Several significant works consistently call for system design methodologies and reiterate the lack of industrial implementation. Some design methodologies do exist but have shortcomings in certain areas or are limited in scope where some do not cover enough processes in the design phase to be considered complete. Future methodologies should support inclusion of reconfigurability characteristics early in the design process and bear a holistic view relevant to the multidisciplinary nature of system design. The following section will endeavour a deeper search for a suitable DM.

3.3 Search for Existing RASDM

Absence of RAS industrial implementation is due in part to a general lack of a complementary system design methodologies which is claimed by several researchers. A DM is needed to systematically include reconfigurability in the system design phase and manage the added complexity. Encouragingly, researchers claim possibilities of adapting existing methodologies (Rösiö & Säfsen 2013). RAS research has yielded an extensive suite of technologies, tools and techniques which advocates derivation of a complete RAS DM. Thus follows Objective 5 to identify and compare different design methodologies. The search is conducted using the industry requirements to guide selection of appropriate research. The review finds that requirements are not satisfied by a complete methodology but are partially satisfied by an automotive RASDM. A number of separate methods and principles satisfy the remaining requirements. A new methodology could be developed by adapting the automotive DM to aerospace and adding the additional features to satisfy the complete set of requirements. The following sections deals with the search process and the accompanying critique of literature.

3.3.1 Search Rationale

Since requirements of an Airbus DM are already defined, several stipulations are followed in an effort to closely scrutinise literature for selection. The use of Airbus DM requirements to guide a literature search inherently disregards unsuitable methodologies, avoiding unnecessary trial and error. As a general lack of design methodologies has already been cited, the search will cover two areas. A primary search is conducted for specific RAS design methodologies to find the nearest workable approach for RAS design. Including consideration of generic RMS methodologies which may be potentially applicable. A secondary search will review individual methods, tools, principles and observations regarding RAS design. Relevant literature is compared with the Airbus requirements for a DM to highlight knowledge gaps and implications for research design. Additional criteria are also used for efficient searches; mentioned as follows. Methodologies with production examples take precedence because a methodology will be used for Airbus RAS design. Naturally, methodologies that don't meet requirements are disregarded. Reconfigurable assembly is classified as a systems design problem so searches are limited to this field. The search is focused on assembly and manufacturing systems design as is the current practice

at Airbus. Search terms are English language only and drawn from the research questions, objectives and aims documented in Chapter 1.

3.3.2 RAS Design Methodologies

A review of works stated as RAS or RMS design methodologies is presented in this section. Rösiö (2013) claims a general lack of design methodologies for industrial use but states existing methodologies could be adapted. The review finds a continued lack of application to industrial problems among published works; which were reviewed against the Airbus DM requirements presented in Section 2.5. However, recent publications by Al-Zaher *et al* show a DM implemented for automotive BiW assembly. The research is studied in detail for application to Airbus assembly and satisfaction of the DM requirements. Additional methodologies found to be unsuitable are cited with justification. The following paragraph covers the Al-Zaher *et al* research and the discarded methodologies discussion follows.

3.3.2.1 RMS Design Methodology for Automotive Framing Systems

Al-Zaher *et al* (2013) present a RASDM used to implement a RAS system for BiW assembly. The methodology is implemented in three industrial case studies for assembly of mixed body styles. The methodology used Axiomatic Design (AD) and Design Structure Matrices (DSM) to design and model the RAS and its changes. AD is a system design methodology which provides systematic and scientific basis for making design decisions (Suh 1990; Suh 2001). DSMs are a system modelling method used to represent interactions between elements comprising a system by assigning components to matrix elements and mapping interactions (Steward 1981). AD is used by the system designers in the early stages to clarify system constraints and product and process characteristics which then inform detailed system design. DSMs are used to model reconfigurations in response to changes to body styles by using DSMs to model corresponding tooling components and body subassemblies (Figure 47).

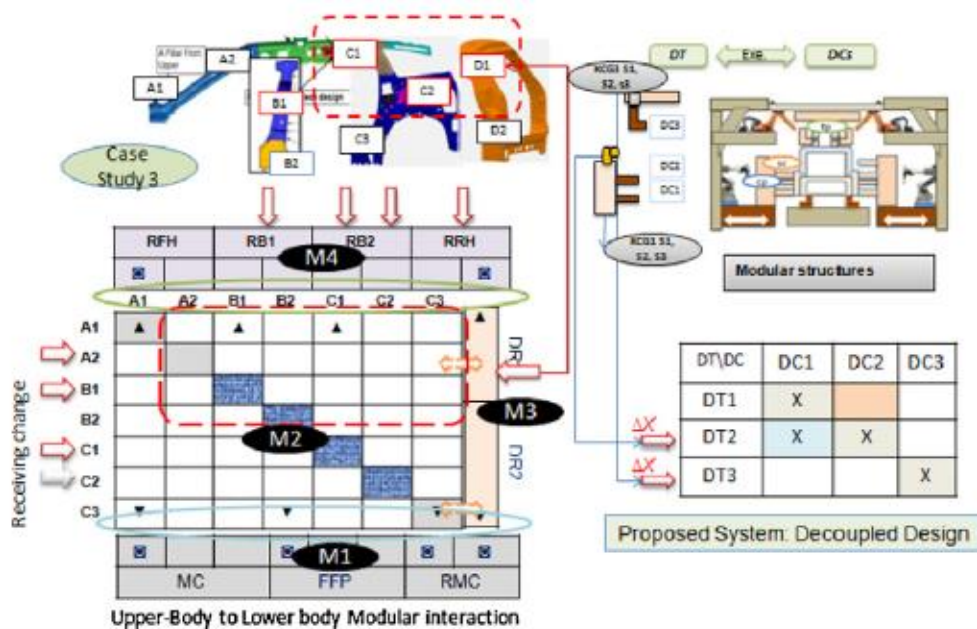


Figure 47. DSMs are used to model physical interactions between subassembly products and the assembly system to manage reconfigurations (Al-Zaher et al. 2013)

The previous dedicated tooling and new reconfigurable system are presented in Figure 48. The current practice is non-reconfigurable and previously used dedicated gates for each style whereas an RAS has been demonstrated by using one gate which has been designed to reconfigure using the methodology. Despite 30–50% higher initial investment in equipment and tooling, savings of up to 50% for each new style addition and lead times are reduced by up to 80% (Al-Zaher et al. 2013). The methodology was applied again by Al-

Zaher & ElMaraghy (2014) for an underbody RAS Figure 49. The methodology was applied to increase the number of variants that can be produced using a single production system and mapped physical interactions between body and underbody domains as well as assembly tooling. Researchers claim up to 50% cost reductions.

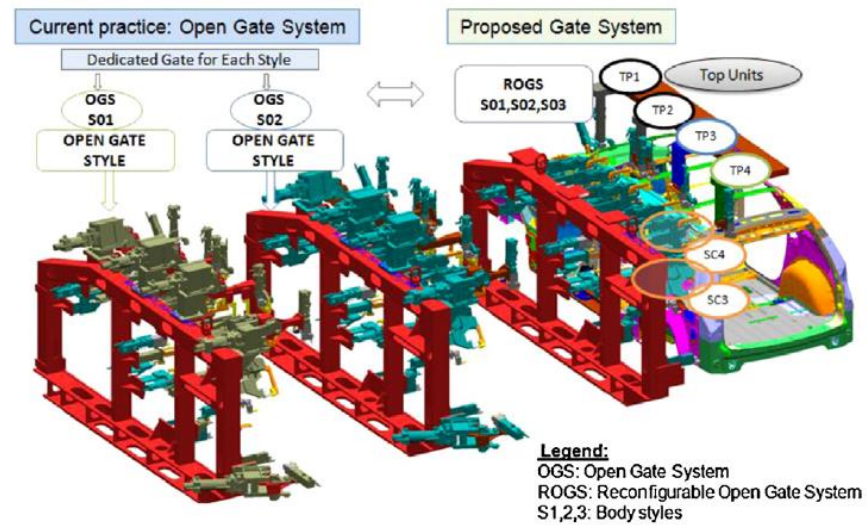


Figure 48. RAS DM has been used to propose a new system which reconfigures to each new body style rather than commissioning dedicated tooling for each body (Al-Zaher et al. 2013)

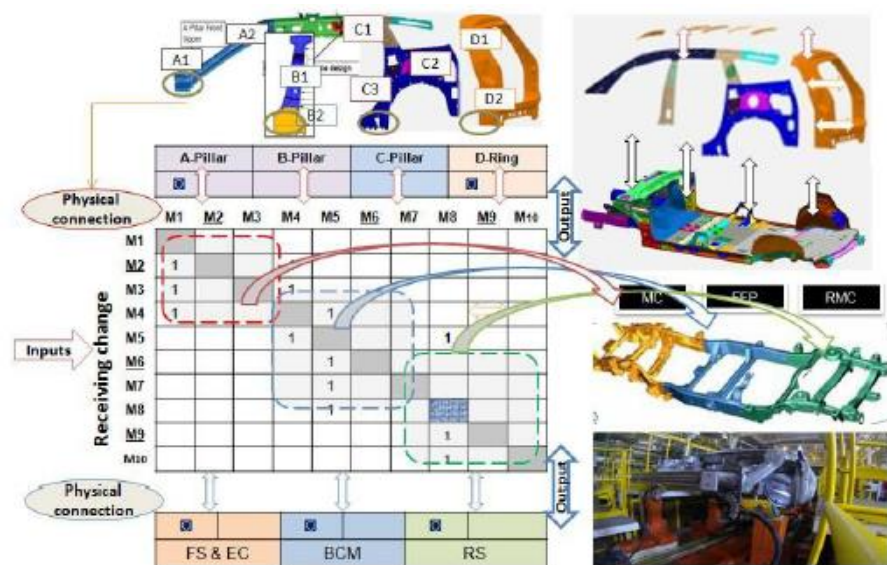


Figure 49. DSMs are used to model physical interactions between body style, underbody and the assembly system (Al-Zaher & ElMaraghy 2014)

3.3.2.2 Analysis

A RASDM has been developed and implemented successfully for an industrial RAS for automotive assemblies. Brought about to address the current systems which are difficult to change in response to customer demand, akin to Airbus assembly systems. The proposed methodology satisfies a number of requirements for an Airbus DM. It deals specifically with industrial implementation and relies on designer knowledge and expertise which indicates compatibility with Airbus practices. The use of AD and DSM structures the design process and identifies physical interactions and can be used to model reconfigurations. Industrial case studies are used to develop 3D models in the design phase.

Despite the advantages, key areas of the methodology are limited or absent. The publications provide no details on specifying reconfigurability requirements. This is essential to Koren's (*op. cit.*) definition where systems should be designed from the outset for scalability. However, it is clear that AD has been used to specify the functional requirements for variety and appears to be successful. Values for reductions in lead time are cited but there is no mention of ramp-up. Likely this is because automotive applications are focused on mass customisation. In this instance, scalability has not been demonstrated. In relation, only physical interactions are mapped using the DSM. Possibly due to automotive needs here which may only be concerned with tooling changeover. Of course, there are many interactions in a system. For aerospace applications where scalability is concerned systems will have to change in structure which has the added complexity of adding automation which has impacts throughout the system such as process changes and proximity to other systems. More in depth interactions across multiple domains may be necessary for aerospace design and reconfigurations.

Other general concerns are the dependence on designer knowledge which the researchers acknowledge can cause difficulty. This shouldn't be any more of a problem than it is currently at Airbus which relies on multi-disciplinary collaboration of engineers. The automotive examples presented are better suited to automation thanks to years of model revisions. Most commercial structures are predominantly manual assembly and automation is only recently being adopted. Though it could be argued that the scientific basis of AD means the methodology could be readily applied to designs with manual processes and aerostructures.

3.3.2.3 Alternative Methodologies

Al-Zaher methodology most closely matches Airbus requirements for DMs and is mature enough for application because of the industrial implementation and detailed design. Other design methodologies were reviewed and are presented here with justification on unsuitability. Alternative methodologies are available and address some of the key issues in RAS design but are generally unsuited to particular needs of Airbus. This is perhaps due to most research approaching from an academic standpoint rather than an industrial standpoint. Numerous shortcomings were found in other methodologies in relation to compatibility with Airbus. Weaknesses were also evident for implementing scalability and 3D design. Each methodology is discussed in turn.

Lohse *et al* (2005) present a holistic equipment ontology that defines assembly modules according to requirements and constraints. Extensive ontology modelling of equipment is used to design RAS in highly modular fashion for part family or demand change. Much of the design process is automated which reduces design effort (Lohse *et al.* 2005). For Airbus, this presents greater challenges to certification where each module will require certification which is unfeasible for costs and lead time. Aircraft tooling is mostly bespoke and does not lend well to modular assembly at this stage but could be a long term solution. Another rule-based system uses a capability model and taxonomy to select modules and reconfigurations to suit assembly process requirements (Smale & Ratchev 2009a; Smale & Ratchev 2009b). This is also has potential for long term development with its integration of DFMA but currently does not offer the necessary insight into 3D design and system integration as seen with Al-Zaher (*op. cit.*). A similar assembly process design approach share a similar approach (Fujimoto *et al.* 2003). Several Algorithmic methods are proposed elsewhere to model RAS (Lee 1997; Yu *et al.* 2003; Siddiqi & de Weck 2008). These are better suited to a more mature set of complimentary modular products and systems. Siddiqi & de Weck (2008) do include some additional design principles to guide development. An integrated approach to design is presented for flexible manufacturing systems (Borenstein *et al.* 1999). While FMS work on a different principle to RMS, the systematic multi-criteria approach is potentially compatible and is intended for use by a design team. Unfortunately it lacks the necessary modelling and implementation of reconfigurations brought about by change in structure. A methodology is used to define a reconfigurable assembly system architecture for a family of heat exchangers (Mesa *et al.* 2014). Clustering algorithms group similar processes and parameters for assembly much like Smale & Ratchev (*op. cit.*). Reconfigurability characteristics are applied using an

Analytic Hierarchy Process (AHP) model. AHP is also applied by other researchers (Abdi & Labib 2003; Abdi 2009). The AHP method prioritises design criteria by normalisation techniques. For an Airbus application this would have to be supplemented with some methods for implementation and detail design as well as reconfiguration modelling. Design lessons and recommendations are made from a long-term research project (Newman et al. 2000). The work is concerned with quick implementation of cost-effective assembly tasks. Efforts present investigations into flexible gripping and handling for a variety of components rather than increasing capacity though the systems appear to be scalable by duplication. The work is not a methodology as such but has valuable insight for implementation with recommendations made for hardware and software design. A similar methodology based on Axiomatic Design principles is applied to cellular manufacturing design which shares some similarity with a reconfigurable system (Kulak et al. 2005). The decomposition approach is apparent elsewhere in ASD which states the importance of understanding system interactions. Industrial examples are presented for a DM for product variety (Hu et al. 2011). A decomposition approach for manufacturing system design is put forth to address the lack of system interactions (Cochran et al. 2001). Again, the specific needs for including reconfigurability characteristics are lacking. Though, the approach could feasibly be applied to decompose requirements for functionality and capacity using AD as applied by Al-Zaher (*op. cit.*). Details are still lacking on dealing with physical integration issues such as interface design and process planning.

More recent works have emerged to address the needs for scalability and a more comprehensive methodology. Mobile manufacturing is investigated directly and put forth into a design framework (Benama et al. 2014). The importance of the mobility characteristic is stressed specifically for capacity change. Issues associated with managing mobile systems are discussed for design. The proposed design framework extends from requirements capture to downstream implementation. The inclusion of capacity in design is directly applicable to Airbus. However, the framework can be loosely interpreted and doesn't specify a systematic design approach nor system interactions. Although, a systematic approach to changeable system design is evident (Francalanza et al. 2014). In this paper, the need for design methodologies is reiterated, as is the fragmented state of RAS design research. A systematic approach is proposed, beginning with requirements formulation. The second step is synthesis of design requirements by system designers combining equipment components into a connected system. The researchers state this is where reconfigurability is determined by make no recommendation on how to do this other than derivation from requirements. Final stages are simulation and evaluation before investment. The framework is a rational approach with a simple case study but lacks the key details on implementation and how to satisfy requirements in the synthesis stage. Overall though, the framework is applicable to Airbus given extra research. A comprehensive framework for system representation is set out (Benkamoun et al. 2014). As with the previously cited works, requirements are set out firstly for translation into physical designs. The system is treated as a hierarchy of elements and is decomposed into functional requirements and components. The research recommends the use of AD and DSM as design tools; as put forward by Al-Zaher *et al* (*op. cit.*). Though the work fails on giving insight into system interactions and instead uses hierarchical taxonomies which would likely be incompatible with Airbus and the tacit knowledge employed by engineers. The framework is acknowledged as only a preliminary step in RAS research citing absence of reconfigurability enablers. Which, is a particular problem for an Airbus methodology with specific requirements for scalability in designs, though the framework is applicable in general.

3.3.2.3.1 Summary

Several insteps have been made in the field of RAS design which take various perspectives on how to best address the design problem. Several researchers advocate a decomposition approach whereas some researchers have proposed algorithms and ontological methods. More recent works acknowledge the need for system-wide methodologies and propose holistic design frameworks. Al-Zaher (*op. cit.*) is the most mature; demonstrating industrial implementation for automotive but lacks scalability and only has partial systems interactions. The methodology does rely on design experience which is appropriate for

Airbus but still lacks structured requirements formulation. Specific knowledge gaps are defined through detailed discussion in the next section.

3.3.2.4 Knowledge Gaps

Despite the advances in RAS design, the body of knowledge is missing essential insights for Airbus application. Knowledge gaps can be categorised into four distinct areas:

- Use of existing data and designer knowledge
- Specifying Scalability and Customisation architecture
- 3D design and interactions
- Modelling and implementing reconfigurations in industrial setting

Firstly, guidelines on specifying assembly system requirements lack suitable depth for Airbus. Airbus ASD must include a carefully considered mixture of product requirements, existing knowledge and innovation.

The second key insight is in relation to the first knowledge gap. Airbus design practice is deeply dependent on collaboration between engineers who rely on knowledge and experience. Some current design methodologies acknowledge the system designer as central to the design process but provide no reference to knowledge use. An Airbus RAS will add extra complexity in design and operation so knowledge use should be maximised for best chance of success.

Thirdly, there is distinct absence of scalability consideration in design; despite acknowledgement in recent research. This may be partially due towards the mass customisation trend. Airbus require RAS to specifically address the issues of ramp-up and capacity and so should be a formal inclusion in the DM. Scalability consideration in design can be associated with the first knowledge gap since capacity is fundamentally a requirement.

Finally, with the exception of some automotive examples there is little contribution to physical implementation of full-scale production systems. This is perhaps due to cost and time constraints. However, the reviewed methodologies offer little provisions for detail design which is of consequence at Airbus where virtual models are critical and a significant portion of the design phase. What is needed is clear system interactions between components and domains to support design and reconfigurations. Changes to structure not only require modification to the immediate physical architecture but have affects throughout the system. This information is needed for design to develop modular architecture and interfaces and also for reconfigurations to model reconfigurations bought about by changes such as ramp-up. This concept is acknowledged by Al-Zaher (*op. cit.*) but only focusses on physical interactions in assembly tooling and so is underdeveloped for Airbus needs. Overall, the methodology developed by Al-Zaher has strong potential for Airbus use because of demonstrated use of designer knowledge and industrial basis. The limitations of the methodology can be overcome with additional innovation.

3.4 Supporting Methods, Tools and Principles

What follows is a review of supportive research which could influence a cohesive DM which addresses the knowledge gaps. A methodology presented by Al-Zaher *et al* (*op. cit.*) has been demonstrated for industrial RAS design but possesses some limitations for Airbus application. Each knowledge gap is reviewed in the wider context for assurances of validity and for enhancing the Al-Zaher design methodology for aerospace assembly.

3.4.1 Knowledge Capture for System Design

The importance of designer knowledge was established as a fundamental of Airbus ASD in section 2.2.2.1 yet, a review of RAS design methodologies found only minor acknowledgement. Contrarily, including knowledge as part of a DM is demonstrated for

non-reconfigurable ASDs. One instance uses captured knowledge as the basis for assembly line design (Khan & Day 2002). A Method of capturing assembly process planning knowledge is also investigated (Roy & Williams 1999). Another example exists for aerospace design where undocumented processes are captured from domain experts (Emberley et al. 2007). A similar approach of using knowledge capture sessions is used for multidisciplinary design in aerospace applications (La Rocca & Van Tooren 2007). Use of knowledge as a basis for design was demonstrated re-configurable assembly cells which was implemented into a software-based design tool (Ratchev et al. 2007). A later work specifies a framework for using knowledge to design manufacturing systems early in the design phase (Efthymiou et al. 2015). A framework similar to the ones described could be applied to capture knowledge augmented for RAS design at Airbus which would integrate with current practice.

3.4.2 Scalability

Scalability is one of two essential characteristics necessary for a RAS; the other being customisation. Scalability takes precedence with Airbus RAS design because of the current challenges of ramp-up and production rate. Scalability therefore, is a direct consideration in choosing a DM; yet design methodologies for RAS make little reference to scalability albeit with some exceptions which still lack implementation. Scalability has received increased attention from researchers in recent times where it is now seen as key to enhance manufacturing systems in changing markets, in addition to mass customisation (Putnik et al. 2013). Figure 50 presents a graph of publications using 'scalability' and 'manufacturing' key words. Much of the research appears to be ongoing in an investigative phase without application. Researchers have stated replication and modularisation as two concepts for scalability in reconfigurable assembly lines but lacks any example implementation (Setchi & Lagos 2004). This principle is stated elsewhere for assembly systems which scale can be adjusted by the number of robots in the system. System reconfigurability can be further improved if a robotic system itself has been modularised (Bi et al. 2007). The importance of designing from the outset is restated by Wang & Koren (2013) and offers a set of design principles (Wang & Koren 2013). Similar principles can be found elsewhere which seem to focus on machining rather than assembly (Katz 2007).

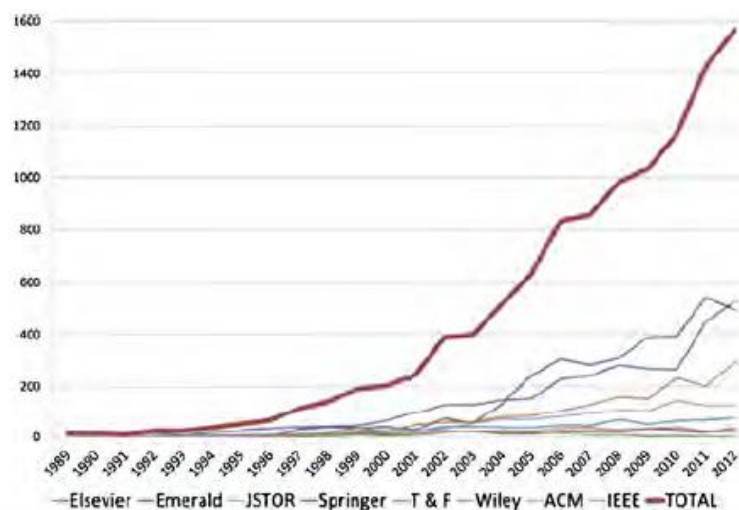


Figure 50. Graph of publications using search terms 'scalability AND manufacturing' in engineering journals (Putnik et al. 2013)

Scalability principles are discussed by several authors which make reference to the work of Fricke & Schultz (2005) which seems to offer the accepted understanding. Scalability gives the system the ability to increase or decrease capacity to match market demand. Scalability occurs in two ways, presented in Figure 51. One way is increasing a single parameter such as motor speed. The second way is by designing a scalable architecture where adding an identical element increases production rate. For Airbus reconfigurable assembly this is likely to be adding additional assembly robots or operators.

Scalability is an ongoing area without much formal work for assembly and researchers are still making observations. Governing principles are available for designers but much research has focused on machining. Still, there is little discussion of the rationale behind applying the principles to problems such as where best to apply scalability in a system and to what granularity of module size. Possibly due to difficulties in designing suitably modular interfaces for assembly system structures. At very least, these principles could be accounted for consideration in an Airbus DM to address ramp-up and capacity challenges.

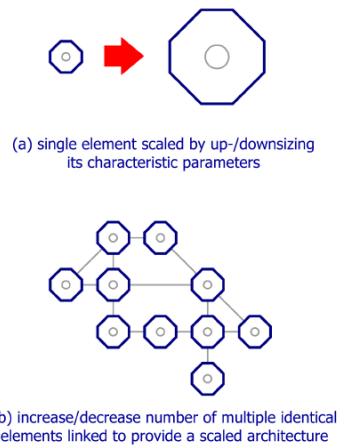


Figure 51. Scalability principle (Fricke & Schulz 2005)

3.4.3 RAS Requirements

The first task of RAS design is to determine the system requirements, i.e. the system capabilities for capacity and functionality (Bi et al. 2007). Most existing design methodologies begin with a requirements definition process, also specified in several frameworks (Benama et al. 2014; Francalanza et al. 2014; Benkamoun et al. 2014). While offering structure to the complete design phase, a formal process is lacking. This is critical because of the 'design from the outset' definition which means reconfigurability characteristics need to be expressed or considered in some way at the start of design. A few researchers have acknowledged this and taken steps to formalisation. The problem is addressed directly through development of a knowledge-enriched methodology for reconfigurable ASD (Hirani et al. 2006). The methodology utilises customer and system integrator knowledge to specify system requirements in order to build reconfigurability characteristics into the system at design outset. Al-Zaher (*op. cit.*) utilises AD decomposition to decompose customisation requirements. Uses AD to decompose customisation requirements. AD uses a hierarchical decomposition process to translate customer needs into functional requirements and physical parameters. The decomposition process incorporates designer knowledge to make design decisions in a systematic manner.

In summation, requirements are what the assembly system must satisfy. Therefore to be considered reconfigurable the system must satisfy capacity and functionality requirements. Requirements are influenced directly by knowledge captured which could be used to specify scalability (and customisation) for decomposition. For Airbus applications, scalability could be included through explicit requirements to fit the definition to design from the outset. RAS requirements could be expressed in a similar way and use a framework to manage the complexity and structure to best capture knowledge.

3.4.4 Detail Design & Modelling Reconfigurations

System modelling is important for detail design and redesign brought on by changes to the assembly system to increase production rate. The designer's task is to create a working system which meets the system requirements. This is made altogether easier by tools methods which manage the complexity and allow the designer to focus on components systematically. Equally so, changes to complex assembly systems such as Airbus initiate

many changes to the system which propagate beyond the tooling interfaces. Again, modelling reconfigurations is intended to support the design team in visualising these changes for assessment and appropriate action. Much research is focused on automating the reconfiguration process but are non-existent for assembly large components. Al-Zaher (*op. cit.*) uses DSMs to map changes by noting physical interactions between components and the corresponding tooling. This highlights which parts of the assembly system require change and is used by designers to reconfigure the system. While the method is suited to managing mass customisation challenge complexity, it is less suited to scalability for Airbus where production rate would likely be increased by adding automation systems. Such a task would incur more changes in different domains and the Al-Zaher method would lack the necessary interactions to represent changes to process documentation, operator manuals, robot paths, spatial location, scheduling, etc. However, these interactions could be included in an adapted DSM model. Eppinger & Browning advocate use of DSMs for mapping interactions between domains i.e. interactions between product, process and system for greater detail into system behaviour (Eppinger & Browning 2012). This could be used for Airbus to show interactions between Product, Process and System. Indeed, this is an existing structure for formalising manufacturing system data (Colledani et al. 2009; Tolio et al. 2010). In regard to specific interactions for reconfigurable systems, Farid uses DSMs to model material, spatial, information and energy interactions to measure reconfigurability in assembly systems (Farid & McFarlane 2006; Farid 2008). Though, applied only to existing systems and not used for design. Given the use by Al-Zaher, it is feasible to adapt the DSM approach to use interactions recommended by Farid and apply to Airbus RAS design. Several researchers have investigated the compatibility of AD and DSM and found them complementary with practical applications (Tokunaga & Fujimura 2013; Tang et al. 2009; Guenov & Barker 2005).

3.5 Conclusion

A search of academic literature finds existing design methodologies have four distinct knowledge gaps. These are: specifying RAS requirements for design including scalability, sufficient use of existing data and designer knowledge, modelling system architecture and modelling system interactions for detailed RAS design for implementation. The methodology developed by Al-Zaher forms an acceptable basis from which to develop a new RAS DM to suit Airbus. The new DM is made up of existing tools and principles incorporated together to satisfy the requirements of a DM derived from the industrial review. Table 6 specifies which Airbus DM requirements are satisfied by each research constituent. Requirement 1 is not totally satisfied by the Al-Zaher methodology because there is no specification of scalability. However, scalability principles used with a knowledge capture framework should elicit sufficient design data to construct meaningful requirements. Translating these requirements into physical designs should then be possible using AD, applied in the Al-Zaher methodology. AD should enable the designer to decompose scalability requirements into a system organised into scalable and non-scalable subsystems to embody reconfigurability characteristics. Requirement 2 is completely satisfied by AD included in the Al-Zaher DM. Al-Zaher does not provide the additional types of interactions nor apply interactions across the system. The introduction of the interactions for RAS outlined by Farid are used across PPS domains. A PPS approach is used in several examples by Eppinger & Browning (*op. cit.*). This combination satisfies Requirement 3. DSMS are used to model reconfigurations brought on by change through the lifecycle of the factory. Modelling Product, Processes and the System enable the designers to see the impacts of change throughout the factory which can be used to calculate costs and time for ramp-up and thus aids decision making for investment (Requirement 4). While the Al-Zaher DM does rely on designer knowledge, the process for gathering the information is ad-hoc and so should be enhanced for aerospace where there is ongoing iterative design between multiple stakeholders. This approach fulfils Requirement 5. The Al-Zaher methodology already has demonstrable systematisation of the design process and so there are no additions for requirement 6. Generating 3D concepts for build philosophies and so on is supported by the addition of the multi-domain

DSMs to inform design of the RAS. Designers can use the interactions to understand practical constraints and construct a working system using real-world equipment. This fulfils requirement 7 where 3D designs can be used by Airbus in broader operations. Requirement 8 is met by adopting a new approach based on a knowledge capture framework which enables the designers to capture a broad range of design data and make formalised use of previous R&D, lessons learnt and best practices. Such information can then be systematically used to influence the system design. Finally, key to implementation is that all methods are readily capable of application to Airbus RAS design since the aim of the work is to develop a working solution for wing assembly.

Table 6. Airbus design methodology requirements

Requirement No.	Requirement specification	Al-Zaher 2014	Farid 2008; Eppinger & Browning 2012	Emberey <i>et al</i> 2007; Efthymiou 2015	Hirani 2006	Fricke & Schultz 2005
1	Specify scalable and customisable capabilities in the design for cost-effective ramp up and model change requirements				✓	✓
2	Identify functional and physical dependencies in the assembly system design	✓				
3	Identify system interactions in the design phase		✓			
4	Analyse impacts of change throughout the lifecycle of the factory		✓			
5	Employ the use of designer knowledge and experience	✓		✓	✓	
6	Systematise and structure the design process	✓				
7	Generate 3D concepts (working principles) early in the design phase to aid decision-making	✓	✓			
8	Consolidate customer needs and existing Airbus data for assembly system design			✓	✓	
9	Compatible with Airbus protocols and documentation	✓	✓	✓	✓	✓

Chapter 4 Research Methodology

Objectives 1-5 were fulfilled in Chapters 2 and 3 which reviewed the current practices of Airbus in order to search for a suitable RASDM. A comprehensive DM lacked some features necessary for Airbus requirements. However, a new methodology could feasibly be created by adapting an existing methodology to include additional methods and principles. The next steps involve objectives 6 and 7 for an ordered process of development, testing and observation of the new DM. The following chapter concerns how the research is conducted as means to answering the research questions. Objective 6 concerns the development of the new methodology suitable for Airbus RAS design application. The new DM is validated by conducting two case studies for two different Airbus wing assembly applications to fulfil objective 7.

The main aim stated in Chapter 1 is to design reconfigurable assembly systems for cost-effective wing structure assembly at Airbus. Therefore, the research methods adopted share this intention. The research is split into two parts: the development of the DM and the application of the DM. The development of the DM follows on from the implications of the literature review and Airbus DM requirements. The case studies continue the research by application to Airbus RAS design projects. The case studies serve two purposes: validation of the DM and contribution to Airbus deliverables. Details of how the development and case studies answer the research questions is discussed accordingly.

4.1 Development of Design Methodology

A review of literature found limitations to RAS design methodologies based on Airbus requirements. However, the requirements were satisfied if an existing methodology could be supplemented with additional features into a new cohesive DM. The new DM is developed according to the Airbus DM requirements presented in Chapter 2. The Al-Zaher methodology was used for the overall structure. Extra details, new steps and methods are added as appropriate with clear rationale, presented in chronological design order for clarity. The methodology was developed and refined iteratively by comparison with Airbus DM requirements. Simplified design exercises were used during development to maintain sight of feasibility. Chapter 5 is dedicated to presentation of this development phase and concludes Objective 6.

The knowledge gaps found in the literature review are tentatively resolved by development of a new DM, pending case studies for validation. The development of new methodology also goes some way to answer the research questions set out in Section 1.9. Questions 1-4 are systematically answered by the outset of a new methodology. Questions 1 and 2 are answered with the first steps of the methodology which structures customer needs and system design to progress design data into a working RAS. DSM modelling methods support detailed system design and reconfiguration modelling to answer questions 3 and 4. The case studies go on to answer Question 5 and validate the methodology for overall resolution of the main research question: How can a reconfigurable assembly system be designed for cost-effective wing structure assembly? The following section presents details of the case studies in relation to implementation and the research questions.

4.2 Case Studies Approach

Two case study applications of the DM from Chapters 6 and 7 to validate the DM innovations presented in Chapter 5. The case studies pursue objective 7 which is to validate the DM by application to Airbus ASD. This section discusses the reasoning for the case studies approach.

The industrial review found Airbus design practices to be complex process of collaboration across multiple disciplines. A follow-on literature review found RAS to be technically feasible but a distinct lack of implementation and shortcomings in design approaches to implement a RAS at Airbus. Thus, designing RAS for Airbus is only practicable through creation of a new DM. Since the aim of the research is to develop RAS for Airbus the focus

is to integrate with current Airbus design not to change design processes, as such metrics are focused on validating the methodology as far as assembly is concerned. A case studies approach is adopted because the methodology can be integrated and applied to Airbus projects. Secondly, case studies yield useable designs for Airbus where real-world data and problems provide realistic scenarios. Thus, the case studies validate the DM for use in an industrial context. Further to this, detailed case studies add research value and knowledge by showing how the methodology is applied from a practical standpoint. Using Airbus data for case studies shows the robustness of the methodology for use within the industrial environment rather than abstract examples. Extra value can also be claimed in that the case studies consider genuine future implementation.

A key aspect of the research is sufficient demonstration of reconfigurability performance to validate the DM and deliver to Airbus needs. Primary metrics are centred around Airbus industrial needs and are cost, production capacity, deliveries and ramp-up time. Metrics are derived from published reconfigurable system performance measures (Mittal & Jain 2014). The methodology will be used to design RAS for two wing assembly projects. Each design will be compared with its respective baseline using the mentioned metrics to quantify the potential benefits of RAS. The first case study concerns future aircraft while the second concerns a current wing. Both use different design approaches, engineers and organisations at Airbus. These key differences tests the flexibility of the DM for different design problems and environments.

The case studies apply the innovations of Chapter 5 to complete the research question inquiries. The structure of the case study chapters follows the structure of Chapter 5 for transparency and future research. Questions 1-4 now have two worked implementations demonstrating each innovation. Question 5 is dealt with wholly by the case studies with respective baseline comparisons taken directly from current Airbus assembly practices. The following two sections discuss each case study in further detail and deal with the unique features.

4.2.1 Case Study 1: Future Aircraft Wing Assembly

The Airbus Next Generation Composite Wing is due circa 2025 or later (*op. cit.*). The design is open and ongoing and will incorporate many new technologies. High-rate production is expected so the assembly system will have to address future ramp-up challenges and the design team must consider a number of potential technologies for incorporation. Future aircraft design is highly iterative and is characterised by tacit knowledge and incomplete data. The case study will be carried out at Airbus to de facto standards with the normal Airbus procedures. This live project will test how the methodology performs in an industrial setting for a future product and test for compatibility with Airbus practices. Naturally, a future Airbus wing is under strict IP restrictions so a structurally comparable model is used and certain product details are omitted where not relevant to the DM. The case study shall be compared to a baseline for demonstrated reconfiguration capability to validate the methodology and system design. The baseline is the Airbus current state-of-the-art assembly practices as described in Chapter 2. A formal TRL2 assessment review is required by Airbus for the ASD which further validates the methodology. Further project details, Airbus deliverables and assumptions are included in the case study presented in Chapter 6.

4.2.2 Case Study 2: Current Aircraft Wing Assembly

The second case study concerns the current A320 wing which has a current backlog of 6193 (*op. cit.*). The methodology is tested for application to a more mature product of older design so there is less consideration of DfA and less flexibility for manufacturing innovation since assembly processes are largely fixed by certification. The ASD should demonstrate reconfiguration capability to address the current ramp-up challenges. A baseline assembly system is modelled to avoid IP issues with the new pulse line. Capabilities are virtually identical but exact figures are protected. Costs are modelled for the comparable pulse line using the non-reconfigurable tooling of the RAS design for closer comparison. The baseline is approved by Airbus to ensure valid comparison, discussed in the following section.

4.2.3 Airbus Design Review

Airbus design reviews are included into the case studies for two reasons. Firstly, design reviews are normal operating procedure for ASD and so validate the methodology for compatibility with Airbus procedure. Secondly, the design reviews enable Airbus scrutiny of the RAS designs and case study findings. Estimations for costs and times are substantiated, as are the baselines. The technical feasibility of the designs and working principles are assessed by Airbus experts. Also, the quality of the designs and build philosophies helps test for compatibility with Airbus procedures.

4.2.4 Limitations

The case study approach and reliance on Airbus design review brings about certain limitations which are highlighted here. The DM is applied to singular scenarios, which are current and selected by Airbus but leaves some uncertainty regarding other possible scenarios. This raises possibility that the DM is only valid for Airbus. However, the thesis is written for future applications and replication. Chapter 5 is structured generically and independent of application. Chapters 6 and 7 contain Airbus specific implementations. Design reviews are limited as far as the knowledge and perspectives of the participants. Detailed limitations are discussed individually for each case study, as are limitations of results. In addition, there is assumed feasibility in other areas of operations such as supply chain, procurement, HR, business, also approved by Airbus stakeholders. This is justified to be acceptable at this stage for discovery of RAS potential at Airbus, as can be the case with many Airbus projects. Nevertheless, the case studies are carried out on an Airbus 'as is' basis meaning the ASD process was carried out as it normally would with the exception of the DM included.

4.3 Summary

Chapter 4 details the DM development and case studies approach in order to answer the research questions. A case studies approach chosen because of similarity to current practice. Metrics for comparing the ASDs with appropriate baselines are defined. Distinction between the two case studies is made as is their significance to validation. Limitations are highlighted noting the possibility of validation being restricted to Airbus scenarios. With the research methodology defined, the investigation can now progress to the development of the DM and case study implementations.

Chapter 5 RAS Design Methodology

Chapter 5 describes the novel RASDM in generic form and discusses each step in detail with associating rationale. The major steps are defined and the essential aspects of each are discussed in detail so that the methodology may be applied in future research. The chapter describes the design data and how it is collected and used in the methodology. The process of mapping is discussed. The DM is then applied to live industrial case studies in Chapter 6 and 7. An overview of the design process is presented in Figure 52 illustrating the translation of inputs to outputs using the RASDM. The methodology combines future needs and existing work to create requirements which are explicitly mapped to physical designs chosen based on designer knowledge.

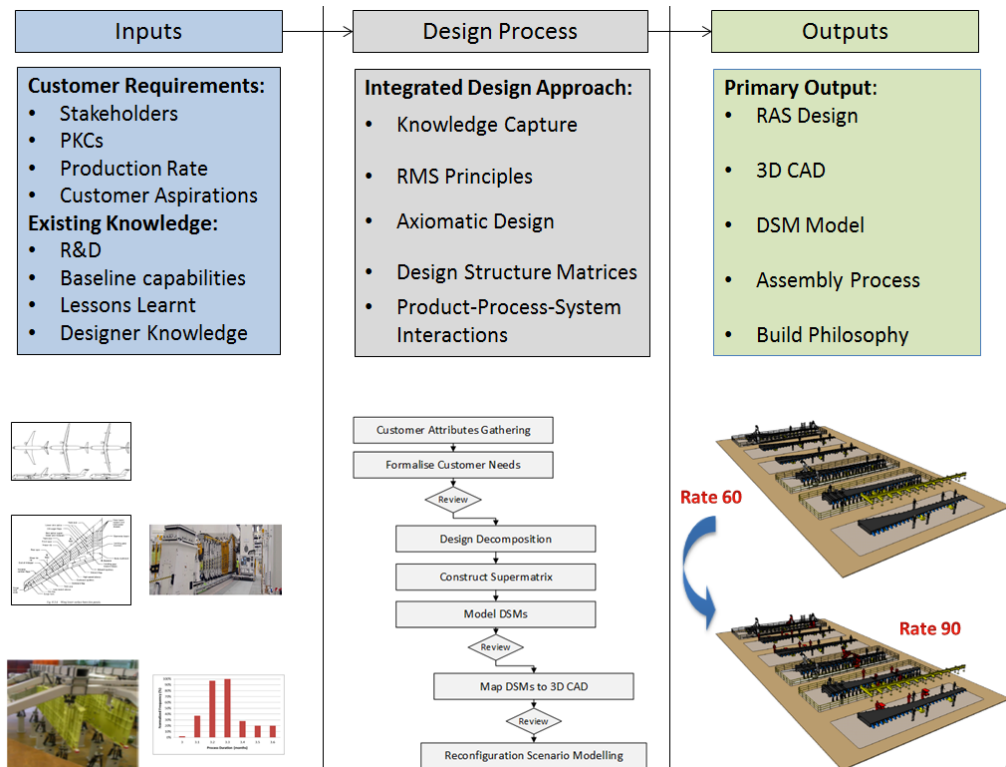


Figure 52. Overview illustration of the RAS Design Methodology Process for aerostructure assembly

Inputs are made up of a mixture of future aircraft requirements and relevant data from previous R&D and current production knowledge to be used. The designer follows the design process (Figure 53) and collects the necessary input data and organises it into meaningful Customer Needs for AD decomposition. Requirements for customisation and scalability are expressed based on the customer needs so that they may be satisfied by physical solutions i.e. exactly the capacity and functionality needed where needed. The AD hierarchy and supermatrix are used to model a PPS DSM of the assembly system. On stakeholder approval, the PPS DSM is used to inform detailed design of 3D CAD. With a matched PPS DSM and 3D design, reconfiguration scenarios can be tested by adding or modifying elements of the DSM and mapping the changes to the system. The cost and time associated with the changes can be calculated and used for reconfiguration decision-making. The primary outputs are the CAD designs of the assembly system plus the assembly process and DSM model for modelling reconfigurations. The build philosophy contains the capabilities and cycle times. From the build philosophy, operational data can be calculated such as NRC and RC and factory volume and footprint. The build philosophy can also be used by other departments to inform decision-making.

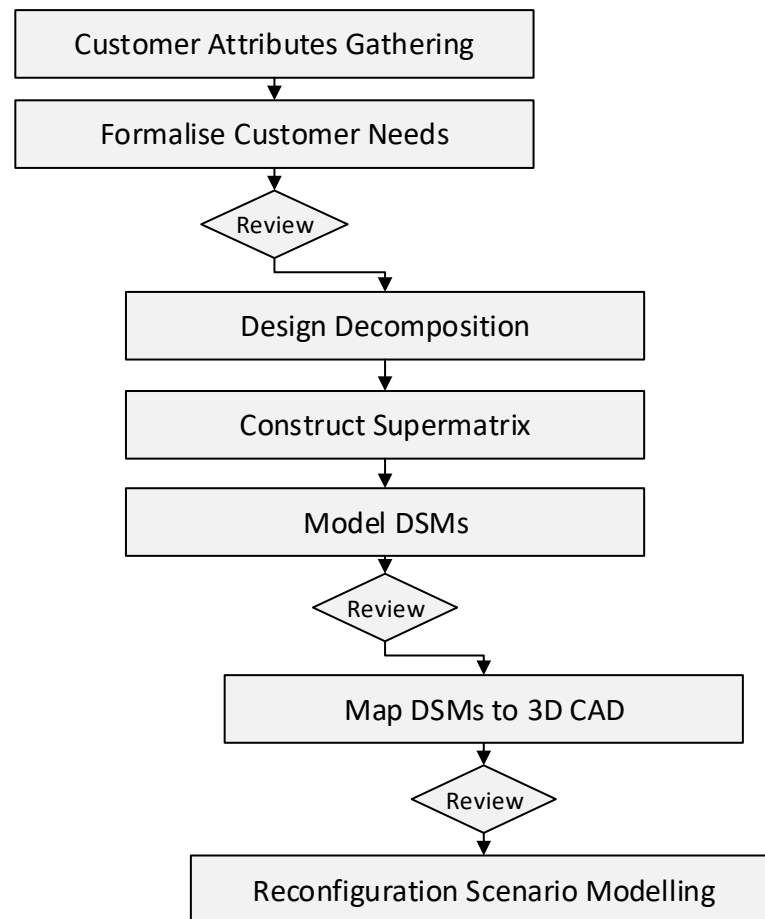


Figure 53. Overview of RAS Design Methodology

Firstly, Customer Attributes Gathering collects mixed quality data through collecting documents and knowledge capture according to a framework to make certain that all the relevant design information is available to the designer. The data is then analysed and reviewed by the designer by drawing on experience and knowledge to organise the information into a set of customer attributes. Customer Attributes are defined as a mixture of technical requirements that need to be achieved and relevant information that needs to be considered to influence the design. Both of which influence the system design requirements. Customer Attributes are then consolidated into meaningful Customer Needs then reviewed with stakeholders for revision and unanimous agreement. Customer Needs are the formalised aspects of the customer attributes made relevant to developing a system design. The creation of Customer Needs from Customer Attributes ensures the relevant details from all stakeholders specific to RAS design are embodied into system design regardless of whether they are technical or non-technical. The Customer Attributes and Customer Needs processes also build valuable designer knowledge and experience which is useful for the subsequent design processes. Following successful Customer Needs review the designer uses the AD procedure to map Customer Needs to FRs which are satisfied by DPs and eventually constructing a supermatrix. This ensures independent design and that functional requirements specify scalability and customisation where needed for customer needs. The Customer Needs, AD hierarchy and supermatrix are used to model DSMs for Product, Process and System. The interactions between elements of PPS are modelled to inform 3D design and to later calculate impact of reconfigurations. Primary interactions are mechanical, process and proximity. Following a stakeholder review to agree the DSM construction, DSMs are then used to create 3D designs. The DSMs can then be used to model reconfigurations by adding or modifying elements to alter capacity or functionality i.e. change in structure. Detailed descriptions and rationale for each process are explained in the remainder of the chapter.

5.1 Customer Attributes Gathering

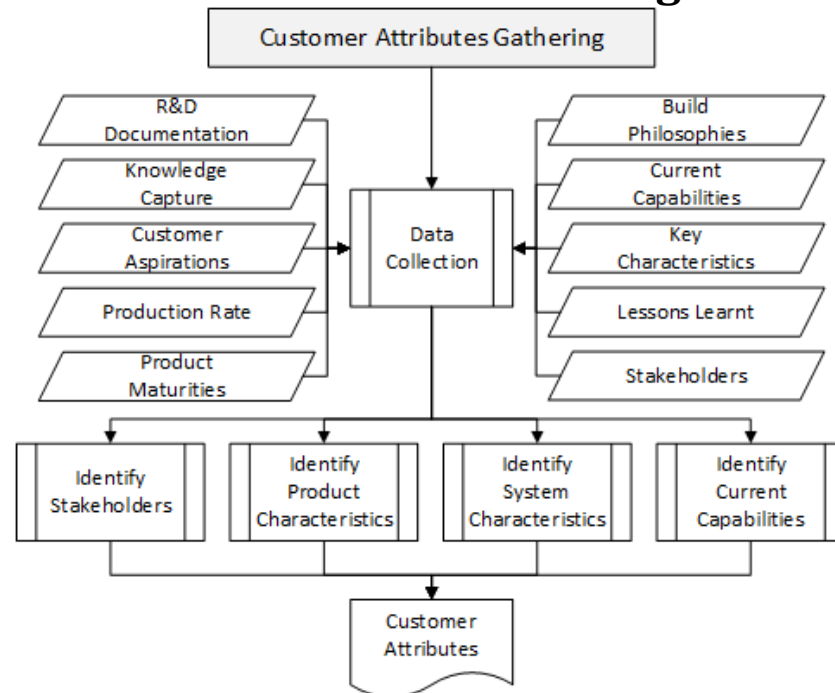


Figure 54. Customer Attributes Gathering framework

The first step of the methodology is to collect all available customer attributes data so that they may be formalised and translated into requirements for design. This is information taken from the customers directly and so is the precedent for designing the manufacturing system and the point of comparison for the system design. Often, customer attributes need clarification with stakeholders and different departments can make conflicting demands. The designer must use this unstructured data to create a set of meaningful Customer Needs for ASD.

Factory design begins before wing design is at full maturity and so design requirements are often incomplete and subject to change. Wing components can be at different stages of the design phase where some are complete and others are yet to be designed. The factory design has to take into account the differing maturities and be updatable for changing products. Similarly, markets and demands can change through the development of the aircraft. The quality of the data captured for customer needs is fundamental to forming sound FRs for which meet customer needs. Dynamic changes and ongoing development mean much of the information needed for ASD is contained in the working knowledge of engineers.

Figure 54 presents the framework to capture the mixed data from all relevant aerospace sources and organise into Customer Attributes for system design. Customer Attributes Gathering begins with data collection of documented data relevant to the assembly system. This is a mixture of future requirements and specifications and existing work carried out to achieve these goals. Typically this is: Aircraft KCs, production rates, build philosophies, TRL packs, build brochures, lessons learnt and R&D technical reports. Technical workshops for additional knowledge capture sessions are required to elaborate on documentation which may only report brief findings or work may still be ongoing. Technical workshops provide the sufficient richness to understand the rationale and direction of ongoing development.

Collected data is then reviewed from an ASD perspective by designers. Stakeholders are identified first for later review stages, followed by Product Characteristics. Product Characteristics are the features and behaviours of the wing itself that influence the system design ranging from fixed data such as KCs to more knowledge-based data such as handling characteristics. The condition of supply at product launch is often uncertain. This

knowledge needs to be captured to influence the FRs and DPs of the RAS design for the most cost-effective solution. Assembly processes are trialled at smaller scale to understand the nature of the products and to test different approaches. Understanding the behaviour of the wing components in a manufacturing environment is critical to ASD because some solutions may be more suitable than others. This information is captured and used to influence constraints and functional requirements.

Manufacturing system characteristics are the customer requirements and aspirations of the factory. Decisions made outside of the manufacturing division at Airbus often have an impact on the manufacturing system design. The data may need to be captured formally from stakeholders and further detail may need to be derived where data is lacking clarity. The data is used as part of the Customer Needs domain and mapped to Constraints and FRs. It is possible for reconfigurability to be expressed here as an aspiration in non-technical terms. Although, the elements that make the system reconfigurable still need proper definition as FRs and corresponding DPs.

Much effort is expended on developing technologies for one aircraft program due to the long times between aircraft launches. As a result it is cost-effective to transfer technologies to comparable aircraft programs. Identifying current captures existing solutions and identify areas for development under R&D. Much of the technologies can be transferred from one aircraft program to another, which is more economical. Current capabilities are also identified for technical benchmarks such as accuracies and variance which influence ASD. Lessons learnt can be drawn from current capabilities of production and R&D to avoid repeating previous errors in production and incorporate promising technologies into a future assembly system.

5.2 Formalise Customer Needs

Customer Attributes are complete with all relevant design data. This information is captured from various levels of engineering, design, manufacturing and management to provide as much richness as possible to ensure the customer needs are complete for translation into physical designs. Customer Attributes are condensed for practical use and consolidated into formal Customer Needs for system design (Figure 55). Formal Customer Needs are later mapped to FRs and Constraints and so this stage is used to check the data for consistency and contradictions and revisited if necessary. The needs for customisation and scalability should be formed from Customer Attributes to be ultimately satisfied by a RAS.

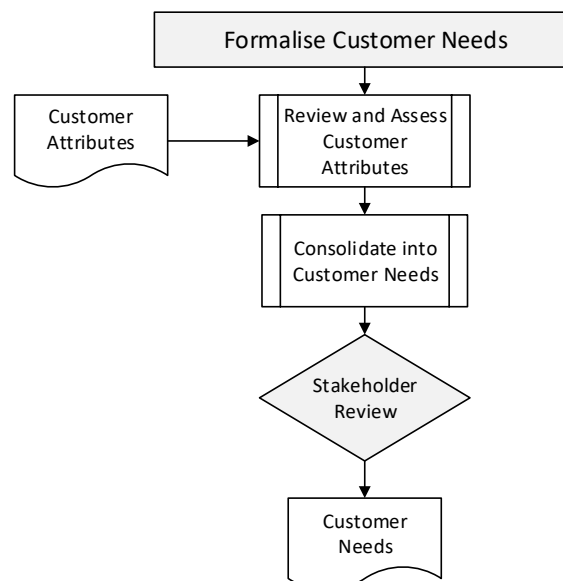


Figure 55. Customer Needs formalisation process

5.3 Design Decomposition

The definitive Customer Needs are used to formulate technical criteria of the RAS. This is termed the Design Decomposition and is presented in Figure 56. The process of specifying scalability and customisation is explained in detail for RAS design. Constraints are the confines on acceptable design solutions that must be satisfied. Input Constraints are explicit to the overall design goals and specified from customer needs. System Constraints are specific to a given design decision created during decomposition (Suh 2001, p.21). Constraints must be specified first to set the technical boundaries on the system prior to design. The data formalised as Customer Needs and Input Constraints can now be used to express the first-level FR of the RAS design. The first-level FR is the starting point from which the entire design is composed. In accordance with AD principles, the design goal should be expressed at the highest level and decomposed to arrive at solution (Suh 1990). For a RAS consistent with Koren's (*op. cit.*) definition, the first-level FR should consist of the following elements:

- Functionality (Operation) - the primary function of the factory
- Part family – a specific range of products, this specifies the RAS characteristic for customisation or convertibility
- Capacity (Demand, ramp-up, rate) - specifies the characteristic for scalability

These are the critical requirements needed to develop a RAS. If these requirements cannot be derived from a constraint or need then a RAS is not necessary. This FR should be consistent with Constraints and Customer Needs. The first FR should be checked for conflict with the Customer Needs and Input Constraints. The first-level FR should completely characterise the functional needs of the system. Since a RAS is a DP, a RAS is only applicable when there are functional requirements for scalability and customisation. The Customer Needs should be traceable to these elements. Customer Needs express functions for quick ramp-up, customisable for product family and evolvable for new variants. These functions bear resemblance to reconfigurable solutions and can be characterised in a single FR. Table 7 characterises the function of the RAS for wing assembly and shows the matching RAS characteristic described by Koren (*op. cit.*). Table 7 presents the customer needs and input constraints mapped to the first-level FR. The first-level FR is a complete characterisation of function of the factory and does not conflict with the customer needs and input constraints.

Table 7. First-level FR for reconfigurable assembly and corresponding RAS functional characteristics

FR constituents for RAS	First-level FR for RAS
Functionality	<i>'Assemble...'</i>
Part family	<i>'...primary structures of wing family...'</i>
Capacity	<i>'...as demand requires'</i>

The Customer Needs and Constraints for RAS are characterised as FR₁ so DP₁ for decomposition into a system architecture with all the necessary functions to satisfy the Customer Needs without violation of the Constraints. Characterising the Customer Needs in this manner leads to the development of scalable and customisable sub-FRs in the system architecture which are embodied by DPs. The methodology later implements DPs as physical subsystems. DPs also must remain consistent with Customer Needs and Constraints according to AD. This process of decomposing functions and design elements in systematic order allows the designer to specify exactly the capacity needed where needed.

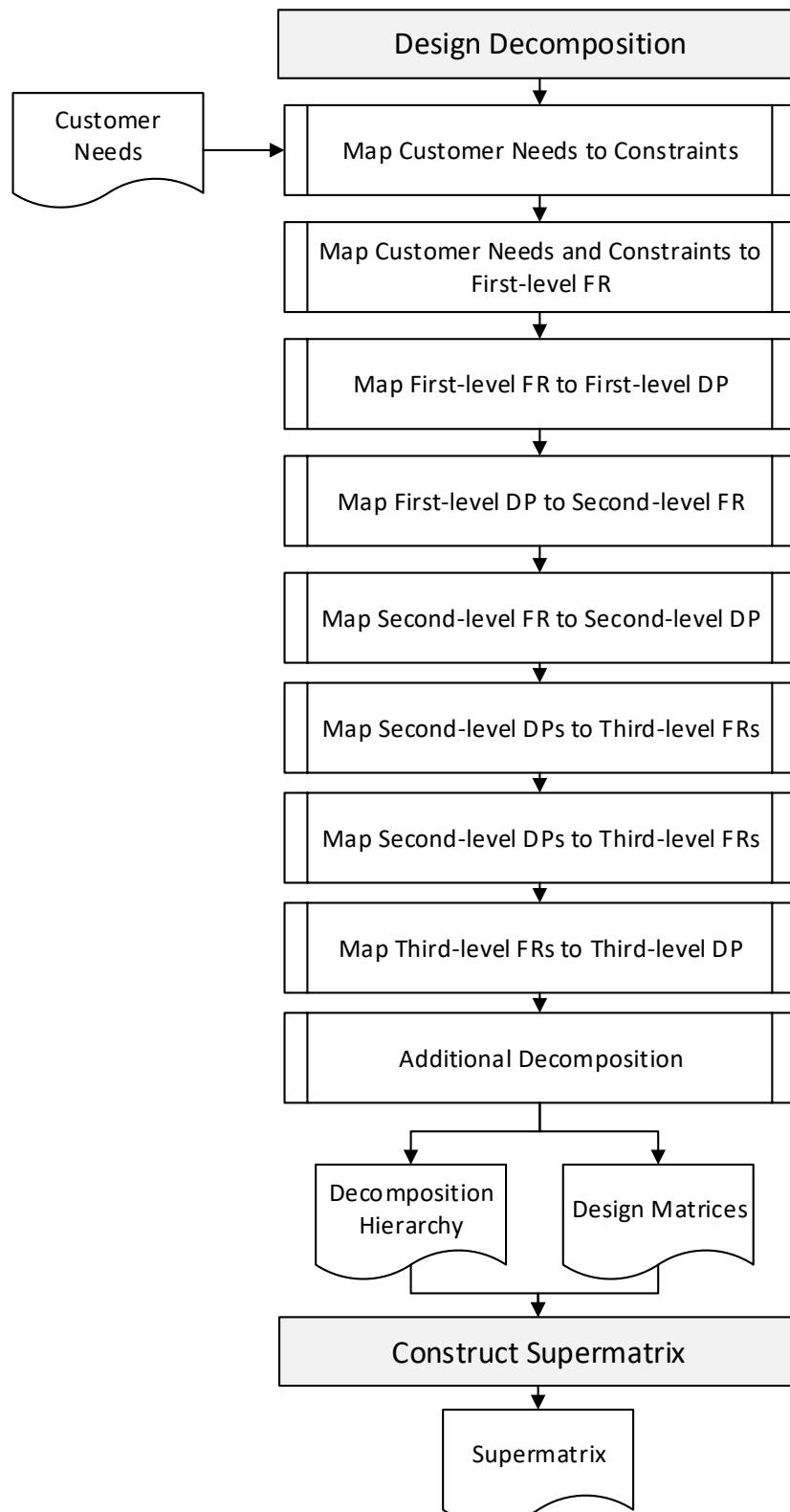


Figure 56. Design Decomposition Process

The first-level DP is the RAS. This DP must satisfy the first level FR; consonant with Customer Needs and Input Constraints. To design a reconfigurable system the first level DP must possess RAS characteristics of customisation and either scalability or convertibility. Specifying these DP characteristics at this level where there is no functional need will lead to a design with extraneous DPs which is at worst a redundant design and at best a waste of financial investment. The DP should not conflict with any of the Constraints and should satisfy the Customer Needs. The characteristics of scalability and customisation are contained in DP1. Decomposition to lower-level FRs must be consistent with the solution expressed in DP1 which ensures reconfigurability is embodied in the detailed design. Customisation and scalability characteristics are embodied in DP1 by translating specific Customer Needs for ramp-up and product family assembly requirements.

DP1 is now decomposed into sub-functions (second-level FRs) which specifies requirements for reconfigurability in more detail in order to give exactly the capacity/functionality needed when needed. Sub-FRs act as constraints at lower levels. Therefore any decisions made at this level affect the design implementation. The Axiomatic Design framework offers little in aiding the designer with zigzagging or decomposition to the next level. Supplementary work is required to do this. This is why there is pragmatic knowledge capture as part of the methodology to aid the designer in developing an effective solution. At this stage, the design team have to (compare solutions) agree a solution because there are several ways in which the sub-FRs can be expressed. Using designer knowledge and Customer Needs information guides the second level FR decomposition to ensure the final design implementation meets Customer Attributes. Physical solutions are now conceived to satisfy the second-level FRs. The second-level FRs can be embodied by several alternative designs since the FRs do not suggest any particular factory layout i.e. the same set of functions can be achieved using a dedicated fixture or a production line. Supplementary work is required to develop satisfactory DPs that best meet Customer Needs.

A design matrix is produced to show the relationships between FRs and DPs. The design matrix is created using knowledge accumulated during workshop discussions for second-level DPs. The design matrix is used to show whether the design is uncoupled, decoupled or coupled. The relationships between FRs and DPs form the constraints for the next level where there is a decoupled design. This suggests that the DPs in question cannot be designed independently. This has been a problem in Airbus where system interactions have not been thought out and the production suffers as a result. Examples (from lessons learnt) include fixture and automation designed in isolation resulting in redesign at the commissioning stages. This is avoided with an AD approach where interactions are identified beforehand and can influence the interaction of design teams. Functions dependent on more than one DP also affect the reconfiguration process where change to one cell affects downstream functions. This means certain reconfigurations may not be possible or further modifications may be necessary to satisfy downstream functions. The greater the independence of FRs the higher the reconfigurability.

Second-level DPs can now be mapped to third-level FRs. The hierarchical process of zigzagging between physical and functional domains allows customised flexibility for specific sub-functions of the system as opposed to an FMS with all possible functionality. Third-level FRs are a mixture of family geometry requirements, variable demand requirements, commonality and non-reconfigurable requirements satisfied by scalable and customisable DPs. Using the AD process, functions for capacity and functionality change can be specified as part of the overall system functions. Thereby specifying exactly the capacity and functionality needed where it is needed. Each second-level DP is decomposed into a set of FRs. The FRs are composed of specifications for part family and rate. Expressing FRs in this way allows the designer to search for DPs that have the specific functionality needed so the final system design embodies RMS characteristics, not FMS characteristics. Third-level FRs need to be consistent with requirements for part family assembly and demand change. One or more FRs must be expressly related to the cycle time, in accordance with the higher level FR-DP for response to demand. It is the designer's choice on specifying FRs relating to demand. Expressing all FRs with scalability potentially

increases cost because of the additional design requirements and moves towards unnecessary functionality. The Customer Attributes information should be used to influence this to apply the necessary levels of reconfigurability. Note that, non-scalable FRs (i.e. dedicated designs) are less likely to require precision components, sensing and automation. The aim should be to reduce the cycle time of the longest processes which requires supplementary work by the designers.

The next stage is to develop physical solutions that satisfy the third-level FRs and embody the characteristics of scalability and customisation. The specific FRs for demand change and part family DPs will be a mixture of non-scalable and scalable solutions. It is up to the design team to develop the best solutions and capitalise on lessons learnt and R&D. The knowledge captured in the Customer Attributes stage contains R&D of potential DPs which needs to be included in the DP development. The Customer Attributes knowledge capture is incorporated into the mapping process. The FRs specifying demand change will be satisfied by DPs possessing scalable characteristics. FRs specifying part family will be satisfied by DPs possessing customisable characteristics. Scalability can be defined as a modular design where adding modules reduces cycle time. Scalable can be achieved through replication or extension. For instance, a crane and lifting fixture has a fixed speed because no design element can be added or subtracted to increase speed. In situations like this where scalability is specified, it is best to design the DP for minimum cycle time from the outset. This is best captured as a Constraint to guide the design team. Certainly, with the nature of aerospace, capturing lessons learnt and incorporating production rate-related R&D should be applied to non-scalable functions to minimize cycle time impact. In respect to axiom 2, scalable systems are likely to have more information. Demand change is specified as an independent function of the cell which will correspond to one or more physical elements that can be cost-effectively replicated which reduces the cycle time. This means one DP must satisfy at least two FRs – perform some function on the part or parts *and* vary cycle time according to demand. Customisation can be achieved with commonality or flexibility. The designer has the option to use a DP common to all product features or a DP that adjusts to suit each different product feature. Of course, this is dependent on the product design. Naturally a DP common to all features has less information content.

Finally, design matrices are constructed from the complete set of third level FR-DPs for each second-level DP decomposition. Designs are checked for coupling as part of the mapping processes and redesigned if necessary. A supermatrix is constructed from all the design matrices to show the coupling in detail. Coupling in the second-level DM is shown in greater detail relating to specific sub-functions. The FR-DP relationships presented in the supermatrix are later used to identify the system interactions for DSM constructions. The lower-level FR relationships shown in the supermatrix are used to conceive process designs for the RAS.

5.4 Model DSMs

With the system design decomposed into FRs and DPs, DSM construction can take place. DSMs are a system modelling method used to represent interactions between elements comprising a system (Eppinger & Browning 2012). DSMs are used to represent many different complex systems for design and analysis. DSMs are modelled for the product (wing), processes and system. DSMs are used for several aspects of the RASDM. Firstly, DSMs are used to help integrate DPs into practical designs. AD does not specify the interactions amongst DPs, particularly physical connections (Tang et al. 2009). The populated DSMs then become the basis for 3D design. Secondly, DSMs are used to map changes in the system resulting from a reconfiguration. This information is then used to calculate the time and costs of reconfiguration. Figure 57 presents the DSM modelling process. DPs are grouped into a system DSM from the AD decomposition hierarchy followed by modelling a product DSM and then finally using the supermatrix to model the process DSM. The PPS DSMs are modelled according to statements made in Customer Needs. Finally, the MDMs are modelled to complete the PPS DSM which is reviewed against Customer Needs with stakeholders. This section covers the detailed description of each stage of the DSM modelling.

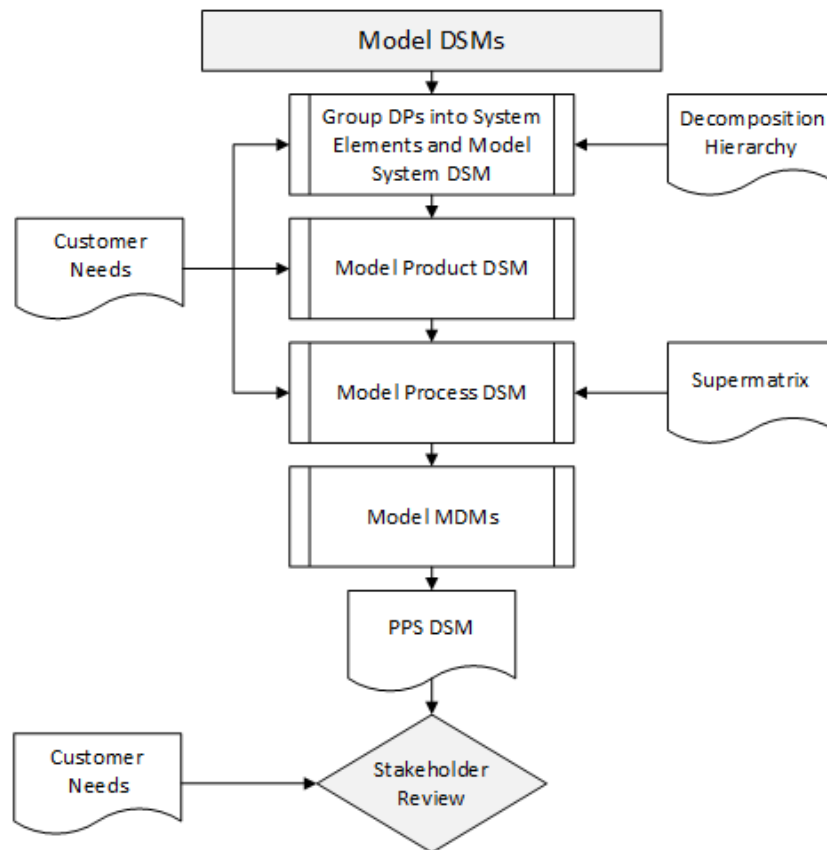


Figure 57. DSM modelling process

The translation of DPs into DSMs is explained. The interactions used for each domain DSM are explained with worked examples for Product, Process and System. Mapping interactions between domains (MDM) is also clarified.

5.4.1 System DSM

DPs should be decomposed until they embody an existing solution or feasible design (Suh 2001). Some DPs need decomposing further to reach a group of physical elements that can be integrated. The interactions between abstract concepts are unclear until they are composed of feasible parts. So, there is a two-step process of further decomposition and then mapping the DPs to existing equipment. The DPs are decomposed until the designer observes DPs suitable for integration. The DPs can now be grouped into system components and represented in a DSM for detailed integration. The designer uses previous experience and Customer Needs data to devise assembly system components consisting of the DPs. Sometimes one DP can be embodied in more than one component depending on particular customer constraints. Tate states that integrating into minimum components reduces information content (Tate 1999, p.48). With all DPs translated into production elements they can be grouped into a DSM. The DPs are now embodied in practical designs elements that can be readily implemented into an assembly system. The system DSM decisions influence construction of the process DSM.

5.4.2 Product DSM

Product DSM elements are made up of the KC features to be achieved during assembly. Wing features are constructed into a DSM to show where dependencies lie and to highlight interactions. Future reconfigurations may involve a change in one or more of these features which affects the processes and manufacturing system. Mapping using DSMs visualises this affect and shows which processes and equipment need modification. The Product DSM is constructed solely from Customer Needs.

5.4.3 Process DSM

The process DSM is created from the product and system DSMs as well as the AD decomposition and Customer Needs. The process DSM contains all the steps to assemble the wing KCs. The process DSM represents the assembly activities and so is only composed of process interaction types. The process DSM modelling method is as described by Eppinger and Browning (2012). Assembly processes are conditional, sequential, parallel or coupled activities. Sequential activities are lower-triangular and upper-triangular markers represent coupled processes where feedback loops are needed e.g. for metrology feedback to actuators for positioning.

5.4.4 Modelling Interactions

In this section the rationale for interactions types is explained. The interactions are to enrich 3D design and plan reconfigurations. There can be many interactions and the DSMs offer this benefit as they can be reused for other problems. In this case, the interactions are limited to those unique to design a RAS. Identifying interactions requires some degree of discussion and input from expert knowledge and designers (Eppinger & Browning 2012, p.23). The DSMs and MDMs use the same colour codes but infer slightly different meanings depending on the domain. The colour code is presented in Figure 58. The following sections explain each interaction and provide an example for each relevant domain.

	mechanical connection/interaction
	Process interaction/information flow
	physical proximity
	unique interaction

Figure 58. Colour codes for DSM interactions

5.4.4.1 Mechanical Connection or Physical Interaction

Mechanical interactions are modelled to enrich 3D design by showing which components need to be designed concurrently. Highlighting elements with a physical interaction streamlines the design process because the designer is aware of the necessary functions and physical integration. There is also potential to create modular interfaces for simple exchange, depending on Customer Needs. Furthermore, when mapping change propagation the affected elements are apparent which informs the designer which components may need redesign. This interaction is defined as any relationship that involves physical contact. Either between two physical elements or, a process acting on or for a physical element. Typically a physical interaction involves a permanent or temporary connection between physical components such as end-effector to robot. For interactions related to processes typical examples include handling parts and involves physical manipulation.

5.4.4.2 Process Interaction or Information Flow

Process interaction involves control or measurement of some variable or parameter. Process interaction notes exchange of information between elements. This can either be the process sequence itself (i.e. process step 1 complete, execute step 2) or actual transfer of information between physical components such as feedback between a robot and positioning system. Information exchange is needed between process and equipment to position, sequence, retract, etc.

5.4.4.3 Physical Proximity

Physical proximity is specifically included to show which elements share space together. This information needs to be shown for RAS design for two reasons. Firstly, designing elements without awareness of spatial proximity may cause clashes in production. Secondly, highlighting spatial proximity is necessary for reconfigurations where equipment is added or changed.

5.4.4.4 Unique Interaction

Unique interaction denotes any other interaction the designer wishes to capture, specific to the application. Examples include heat transfer, vibration, electrical interferences, chemical transfer, energy flow, mass flow (weld material, sealant). A number system can be used to note the number of unique interactions i.e. heat transfer and mass flow for welding which would receive a unique number which could be referenced elsewhere.

5.4.5 MDM Interactions

With DSM construction complete the interactions between domains can be mapped. The interactions between domains inform 3D design integration and acts as a model to identifying system changes from reconfigurations. MDM interactions are made up of physical and process relationships where elements use or act upon each other. Explanations of the rationale for each MDM are explained. Physical interactions between the Product and Process domain concern which processes involve which parts. Process interactions concern information flow such as which feature is measured for a process DSM element. Interactions between Product and System domains are physical only, such that it is a case of which tools act on which parts. Physical and process interactions exist between the Process and System domains. Most prominent of which are physical interactions denoting which processes use which pieces of equipment. Process interactions map information inputs and outputs between equipment and processes.

5.5 Map DSMs to 3D CAD

A PPS DSM is now fully modelled complete with interactions, ready for 3D modelling and build philosophy documentation. Figure 59 illustrates the process for 3D cell design which uses the PPS DSM, supermatrix and Customer Needs to inform and circumscribe detailed design.

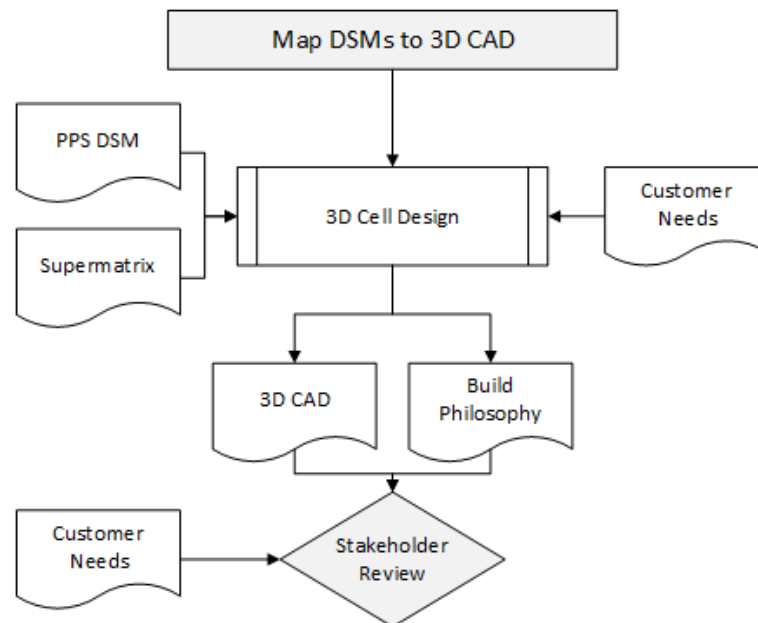


Figure 59. 3D cell design process

The PPS DSM contains all the system interactions of the RAS specified by design and reviewed by stakeholders. The designer proceeds to design 3D components, consistent with the interactions and architecture of the assembly system modelled in the PPS DSM. The interactions modelled in the DSM show where connections exist between system elements and the designer can design accordingly. Since the DSM is derived from the AD hierarchy the 3D designs will embody the characteristics of scalability and customisation specified in the design decomposition. Using DSMs to model the interactions product, process and system means the designer is aware of connections between domains which is useful because component features can be designed for their specific functions in the

system. This allows the designer to focus on the design of individual elements in relation to its relevant functions in the system which reduces the design complexity for the designer thus reducing the chances of design error. The spatial proximity interactions are used to guide design to avoid tooling clashes and also in regard to scalability and reconfiguration. Mechanical interactions highlight where interfaces should be designed in tandem. Process interactions highlight where information needs to be exchanged or actions need to be carried out. Using the DSM, detailed equipment and processes can be designed which embody the characteristics specified in the AD decomposition. Designing the system according to the interactions means the physical system is consistent with the FRs and DPs for scalability and customisation thus providing exactly the capacity needed where needed and embodying the characteristics for RAS.

5.6 Reconfiguration Scenario Modelling

The DSMs are constructed into PPS domains for design integration and system representation. The PPS framework is used to show the relationships inside each domain as well as the relationships between domains.

Relationships can be shown for a single domain such as the physical connectivity of the product elements. Relationships between domains can be shown such as what system elements use which processes. This information is used for reconfigurations to calculate the changes to the system for a given reconfiguration by adding or removing elements and mapping the new interactions.

The reconfiguration modelling process is presented in Figure 60 which begins with the reconfiguration scenario. Either change in capacity or functionality. The requirements for change are analysed by engineers, typically in a technical workshop for exchange of ideas and agreement. The elements of the system which are to be modified or added are noted. This may either be product, process or system depending on the requirements. The PPS DSM is then modified to reflect the modified system and the new interactions are mapped then the CAD model updated. With a new PPS DSM updated to represent a reconfigured system engineers can visualise the implications of the changes and calculate the time and cost to implement. This information can then be communicated to stakeholders for investment analysis.

5.7 Summary

A novel DM is presented to satisfy Airbus requirements for RAS design. The available methodologies are only partially suited to aerospace. The RASDM is presented with supporting rationale and the design process is described in detail for application. Several innovations are used to fill knowledge gaps from the literature study. The first innovation is the creation of a design knowledge framework for capturing knowledge for aerospace RAS design. Secondly, a process to specify scalable and customisable capabilities in the system design is established. The next innovation is translation to physical design by the DSM modelling process for RAS design which highlights system interactions specific to RAS design. DSMs are modelled for Product, Process and System from AD architecture and used for 3D embodiment of reconfigurability characteristics. Finally, the PPS DSM is used to model reconfigurations by adding or modifying elements and then using this information to calculate times and cost to reconfigure.

Table 8 presents the DM requirements from Chapter 2 with the corresponding capabilities of the DM presented in the various sections of Chapter 5. AD and a supporting rationale supplies the means to specify scalable and customisable capabilities from the outset for requirement 1. What's more, AD identifies the functional dependencies in the ASD. However, this lacks the means to highlight physical dependencies and so the addition of DSM provide this function which satisfies requirement 2. The PPS DSM is used for identifying for modelling the interactions mentioned in requirement 3. Modelling system interactions is critical to understanding the impact of changes introduced to the assembly system, particularly reconfigurations. A process for assessing these reconfigurations is defined which satisfies requirement 4. AD and DSM were selected on their suitability for

use by designers. Indeed, AD positively supports the designer's thought process (Suh 1990). The design knowledge framework captures designer knowledge and experience which completes requirement 5. The overall structure of the DM and the systematic AD decomposition process satisfy requirement 6. In support of requirement 7, the PPS model complete with interactions created using the DM enables expedient 3D design because visualised system interactions communicate detailed design information. And by using a systematic process the DM itself reduces the ad-hoc nature of design. For requirement 8, the design knowledge framework of Customer Attributes Gathering and Customer Needs Formalisation provides measures to synthesise conflicting data into meaningful requirements for RAS. Further to this, the design knowledge framework uses Airbus documentation directly and the DM itself allows the designer to easily output designs in suitable Airbus format.

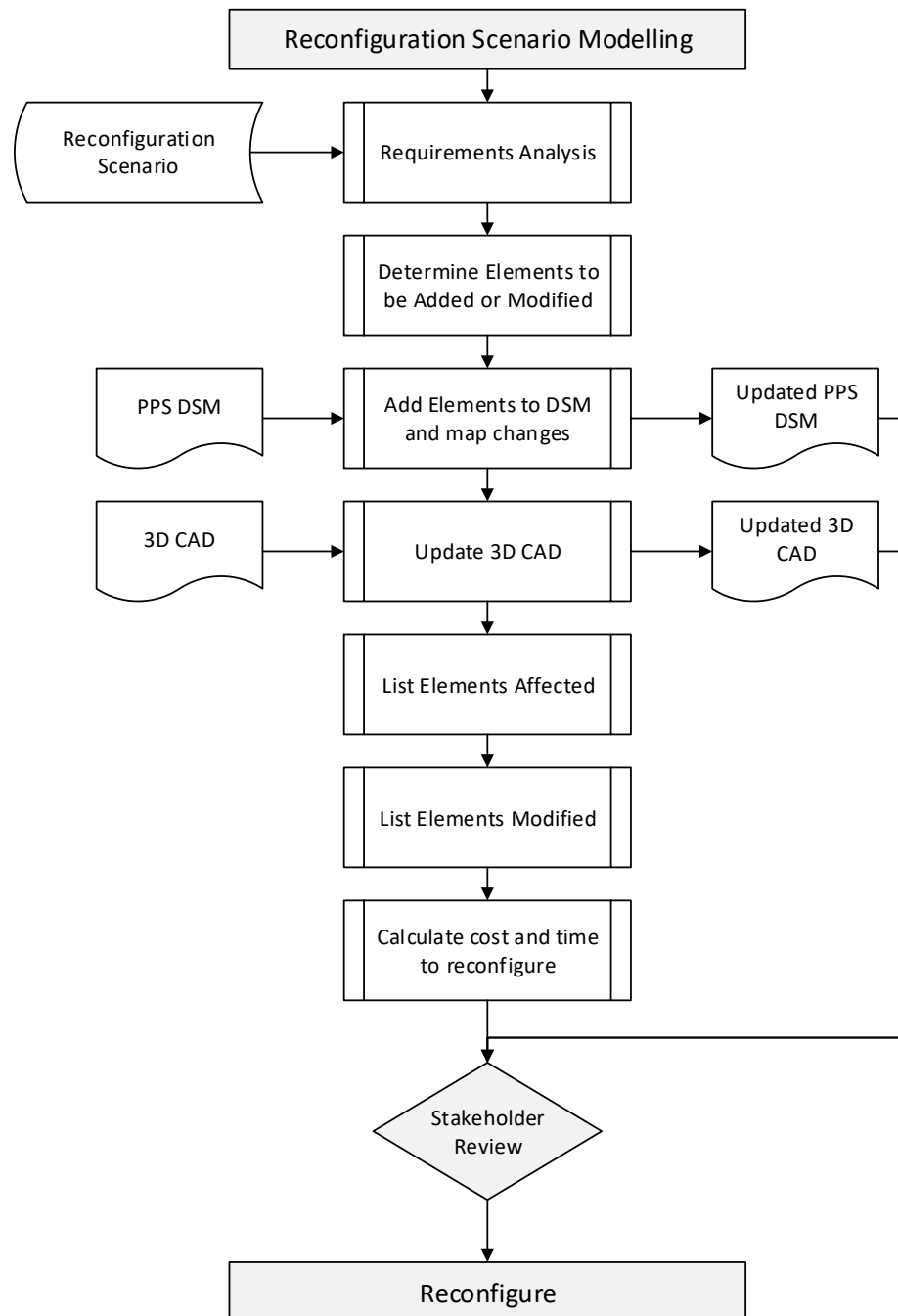


Figure 60. Reconfiguration scenario modelling process

Table 8. Design methodology requirements with corresponding capabilities and the associated chapter sections

Requirement No.	Requirement Specification	Design Methodology Capability	Chapter Section
Requirement 1:	Specify scalable and customisable capabilities in the design for cost-effective ramp up and model change requirements	Axiomatic Design decomposition of Customer Needs for capacity and functionality into corresponding FRs and DPs	5.3
Requirement 2:	Identify functional and physical dependencies in the assembly system design	AD hierarchy, Supermatrix and PPS DSM	5.3, 5.4
Requirement 3:	Identify system interactions in the design phase		
Requirement 4:	Analyse impacts of change throughout the lifecycle of the factory	Reconfiguration scenario modelling using PPS DSM	5.6
Requirement 5:	Employ the use of designer knowledge and experience	Designer-driven methods and design knowledge framework	5.1, 5.2
Requirement 6:	Systematise and structure the design process	Overall Design methodology structure	5.1 - 5.6
Requirement 7:	Generate 3D concepts (working principles) early in the design phase to aid decision-making	PPS DSM for 3D Design Process	5.5
Requirement 8:	Synthesise customer needs with existing Airbus data types and translate into physical designs	Design Knowledge Framework consisting of Customer Attributes Gathering and Customer Needs Formalisation	5.1, 5.2, 5.3
Requirement 9:	Use Airbus protocols and documentation	Design Knowledge framework and Overall Design methodology	5.1, 5.2

Chapter 6 RAS Design Case Study: NGCW Industrialisation

The following chapter is the first of two Airbus case studies of the RASDM. The methodology is applied to ASD at Airbus using Airbus data to validate the methodology for industrial use. A RAS is required for wing production to suit a future aircraft due in 2025. The project and methodology presents a novel step towards RAS for Airbus assembly. Details of each step of the DM and supporting rationale and evidence from the project are presented.

6.1 Project Overview

To demonstrate valid implementation, the methodology was used as part of the industrialisation of Airbus NGCW. The author acted as an Airbus Industrial Engineer in a technical lead role and carried out the industrialisation activities. The project began on June 2012 and the PDR and TRL review were conducted in August 2014. The project goals were discussed with Airbus prior to project launch. The industrialisation is part of a larger concurrent aircraft development process and goals are derived from requirements of Airbus Design, Business and Engineering as well as R&T. The project goals and objectives are defined as follows, elicited from documentation and agreed with stakeholders (Wright & Airbus UK 2013).

Overall goal: 'Design a reconfigurable assembly system for NGCW primary structure for assessment of feasibility and benefits to support Business, Procurement, Design, Engineering and R&T'

Project Objectives:

1. NGCW factory concept consisting of current knowledge and work to date
2. Production rate 60 plus rate ramp-up considerations – rate is main project focus for future production
3. Consider one aircraft configuration based on latest Airbus Design data
4. Understand technical feasibility of tooling concepts for high rate and ramp-up

Project deliverables:

1. CAD factory layout and tooling concepts
2. Airbus TRL2 documentation for Airbus stakeholder PDR review
3. Technical report
4. Assembly process storyboard
5. Manufacturing options matrix

Certain aspects of the system design and process are removed from this chapter to protect commercial property. All aspects pertaining to the design methodology and the academic research involved are included. The full details can be found in Airbus proprietary documents (T. Jefferson & Woolley 2014; T. G. Jefferson et al. 2014; Jefferson 2014c). All design work was carried out by the author as a final authority; acting as technical lead, principle investigator or detailed designer. Work not done by the author is referenced accordingly.

6.2 Customer Attributes Gathering

Customer Attributes are gathered for NGCW and presented with supporting detail. This information is used to form the Customer Needs which is used for system design decomposition. The designer gathers information from all sources by means of analysing existing documents and eliciting tacit knowledge through workshop discussions. Data is then organised into product and system characteristics along with identification of current capabilities. This stage characterises the current state-of-the-art of the program and existing work to date because of the iterative nature of aircraft development. ASD needs the latest data to provide an accurate system that can produce the new aircraft using the latest technologies.

6.2.1.1 Identify Stakeholders & Participants

Table 9 shows the departments involved in the project. For the methodology, it is used to show the origin of the formulated Customer Needs. This is important for project traceability where work is referred to in later stages of the program. Stakeholders also work together to agree assumptions where there is uncertainty. This is particularly necessary in early development. It also defines the contacts for communication in stakeholder reviews later in the methodology.

Table 9. NGCW industrialisation stakeholders

Stakeholders	Department
J Wright	Manufacturing R&D
T Jefferson	Manufacturing R&D
C Turnbull	Supplier - Manufacturing
P Whiteside	Supplier - Manufacturing
P Chivers	Project Management
R Woolley	Project Management
J Price	Design R&D
M Buckley	Manufacturing R&D
M Redman	Manufacturing R&D
T Bryant	Manufacturing R&D
P Green	Design R&D
M Smith	Design R&D
B Heath	Engineering
J Williams	Engineering
T Axford	Engineering
G O'Donnell	Wing Design R&D
R Baxter	Wing Design R&D
D Hill	Wing Design R&D
T Gibbs	Wing Design R&D
D Gore	Engineering
J Dee	Manufacturing R&D
C Mitchell	R&D
F Williamson	Supplier - Manufacturing
R Waring	Supplier - Manufacturing

6.2.1.2 Identify Product Characteristics

The NGCW is in the early stages of development and so much of the design data is incomplete. Product characteristics are identified at the most recent level maturity and used as the basis for assembly system development for NGCW. This step involves reviews of the latest R&D and associated findings. Some technologies may not be taken forward – assembly considers current knowledge and makes decisions based on information gathered. Assumptions are made where necessary and agreed with the stakeholders. Requirements for reconfigurability; that is information relating to model variants and volume ranges are captured.

Wing features are composed of PKC tolerances, frontier drawings and aircraft datum structures. PKC tolerances are derived from aerodynamic performance requirements to

which the assembled wing must conform, presented in Table 10. Frontier drawings are GD&T drawings used to guide design and manufacture for interfacing with other aircraft structures. Datum structures are used to align the wing with the aircraft and support assembly processes. This information is captured for translation into constraints and FRs. For a RAS, product features for all variants are captured to design for part family. If the product is at a low level of maturity (which case with the NGCW design) where future variants are intended but not yet designed then a qualitative requirement can be captured and the system can be designed for uncertainty. Knowledge is captured from stakeholders where aspects of the NGCW are at low levels of maturity.

Table 10. Major PKCs of NGCW wing (Airbus S.A.S et al. 2011)

Study PKC #	PKC Title	Description
1	Mean Outside Skin Profile (LE)	Mean Outside Skin Profile (Forward of front spar datum) for the complete leading edge
2	Mean Outside Skin Profile (Mid-box)	Mean Outside Skin Profile (Between front and rear spar)
3	Mean Outside Skin Profile (TE)	Mean Outside Skin Profile (Aft of rear spar) for the complete trailing edge
4	Step IN LOF (Zone A) All Joints, panels and structure	Steps due to mismatch at fixed structure joints in LOF (Out of wind) and in Zone A
5	Step IN LOF (Zone B) All Joints, panels and structure	Steps due to mismatch at fixed structure joints in LOF (Out of wind) and in Zone B
6	Step A LOF (Zone A) All Joints, panels and structure	Steps due to mismatch at fixed structure joints across LOF (Into wind) and in Zone A
7	Step A LOF (Zone B) All Joints, panels and structure	Steps due to mismatch at fixed structure joints across LOF (Into wind) and in Zone B
8	Lower LE Surface step	All Lower LE steps ILOF, ALOF (+ve value refers to smaller panel sitting proud)
9	Lower TE Surface step	All Lower TE steps ILOF, ALOF
10	Slat to wing alignment upper surfaces	Step between slat top surface tan point and the tan point of the adjacent LE surface
11	Slat to wing alignment lower surfaces Slat 2-6	Step between slat bottom surface tan point and the tan point of the adjacent LE surface on slats 2-6
12	Slat to slat / adjacent structure step at upper surface	Slat to slat / adjacent structure step at upper surface
13	Slat to slat / adjacent structure step at lower surface	Slat to slat / adjacent structure step at lower surface
14	TE Surface to TE moveable step- upper surface	Step between the aileron/spoiler/flap upper surface and the upper surface of TE overhang/panel
15	Spoiler to spoiler step	Spoiler to spoiler out of wind step (in line of flight)
16	TE Surface to TE moveable step- lower surface	Step between the aileron/flap lower surface and the lower surface of TE overhang/panel
17	Aileron/Flap to adjacent movable or structure- upper surface step	Moveable (flap/aileron) upper edge alignment relative to adjacent moveable or fixed structure upper edge
18	Aileron/Flap to adjacent movable or structure- lower surface step	Moveable (flap/aileron) lower edge alignment relative to adjacent moveable or fixed structure lower edge
19	Max Mean Slope - General Surfaces	Rate of change of every surface profile (1 in 200)
20	Max Mean Slope - Joints	Rate of change of every joint surface profile (1 in 100)
21	TE Shroud or Spoiler Lower Surface Spanwise Steps	Step INLOF between lower surfaces of neighbouring panels/spoilers

Aircraft wing design and manufacture is a concurrent process of research and development to bring technologies to full maturity. As a result, the condition of supply at product launch is often uncertain. Understanding the behaviour of the wing components in a manufacturing environment is critical to ASD because some solutions may be more suitable than others. This knowledge is captured for the NGCW program to influence the FRs and DPs of the RAS design for the most cost-effective solution. Various R&D trials assembly processes at small scale to understand the nature of the components. Different methods are tested to understand the variations and how best to deal with this in a manufacturing environment.

NGCW manufacturing R&D includes testing new techniques for composite manufacturing methods, laminar flow wings, optimised structure topology and intelligent avionics. One of the main goals of manufacturing R&D is to find the best solution for production. It is for this reason that the knowledge and lessons learnt is captured to influence the RAS design. Lessons learnt are captured from R&D documentation, TRL packs and workshop discussions. There is inevitable variation in components and some may not reach the intended maturity but are still acceptable for flight and certification. These variations obviously affect the assembly processes and there is a best practice associated. The ways in which these variations affect manufacturing are generally uncovered by R&D trialling assembly processes concurrent with component production testing. The findings are mostly knowledge-based and are elicited through workshop discussions. The product maturity should be captured to influence the RAS design. The information is used to design the RAS to accommodate product uncertainties by decoupling the related FRs and DPs from the rest of the system. The likelihood of change to the product based on its TRL level is also captured. For the methodology, this is used to construct the Customer Needs and Constraints and later to assess the TRL level of the product and system. The product maturity information is captured from TRL review packs. Product Attributes were gathered over a period of months with frequent reviews and workshops with Airbus engineers. The key attributes are captured and consolidated and a summary is presented in Table 11.

Table 11. Product Characteristics

No.	Attribute Captured	Source
1	PKC tolerances – not finalised	Build Brochure Frontier drawings Technical Workshop
2	Assembly datums	Build Brochure
3	Assembly sequence (sub-assembly processes)	Frontier drawings Build Brochure
4	Production volumes – Rate 60 + capability to increase	Workshop discussion
5	Multiple geometric variants	Workshop discussion
6	Engine Pylon geometry undefined - may not be in final wing design	Workshop discussion
7	Main Landing Gear geometry undefined – may not be in final design	Design Workshop
8	Spar cap forming process is TRL2 – process may be abandoned	Manufacture Workshop
9	Limited load can be applied to wing skins when fitting/tacking/drilling	R&D Lessons learnt
10	Composite skins with integrated composite rib feet	Build Brochure
11	Composite spars integrated with lower cover	Build Brochure

6.2.1.3 Identify Manufacturing System Characteristics

Manufacturing system characteristics are the customer requirements and aspirations for the factory. Enterprise-level decisions for strategic, economic and political reasons have an impact on the manufacturing system design for NGCW. Examples include certain factory

footprint size, using certain suppliers and limiting the design to certain equipment types, fewer manual operations, H&S, using existing workforces, ventures into new markets and green initiatives. The data has been captured from stakeholders and further detail was elicited where data is lacking clarity. The data is used as part of the Customer Needs domain and mapped to Constraints and FRs. Reconfigurability is captured as an aspiration in non-technical terms. The elements that make the system reconfigurable still need proper definition as FRs and corresponding DPs, which is done in the formal Customer Needs step. Manufacturing System Characteristics were captured through reviews of documentation and workshop sessions with Airbus engineers. The key attributes are presented in Table 12. Much of the attributes of the manufacturing system required by Airbus were elicited through workshop discussions due to the early stages of aircraft development. Engineers were found to be the predominant source of data for assembly system requirements. Lessons learnt workshops were carried out for existing R&D work and the current A350 assembly system. This allows the designer to take forward preferred solutions and make improvements whilst avoiding deficiencies.

Table 12. Manufacturing System Characteristics

No.	Attribute Captured	Source
1	Composite manufacture and wing assembly in one facility	Build Brochure
2	Minimise factory volume	Technical Workshop
3	Minimise working at height	Technical Workshop
4	Maximise commonality	Technical Workshop
5	Maximise high-TRL 'off-the-shelf' solutions	Technical Workshop
6	Horizontal build	Technical Workshop
7	Increased automation for reconfigurability- mobile automation equipment	Technical Workshop
8	Shorten ramp up time – Airbus directive 50% reduction or greater	Workshop discussion
9	Tool location on non-datum bagging side – fixture does not constrain PKC	R&D Lessons Learnt
10	Lower skin 'sags' in fixture	R&D Lessons Learnt
11	Spar face and spar cap springback – component outside GD&T spec	R&D Lessons Learnt
12	Using spar caps to reclaim spar faces – coupled design	R&D Lessons Learnt
13	Full scale loading concept – redundant design	R&D Lessons Learnt
14	Rate 60 Operations R&D – rib setting and positioning not within cycle time	R&D Lessons Learnt
15	Variations in manufacturing and tooling prevented hole-to-hole assembly	R&D Lessons Learnt
16	Stack slippage after bolt removal for pylon drilling	A350 Lessons Learnt
17	AGV speeds limited by H&S affecting process times	A350 Lessons Learnt

6.2.1.4 Identify Relevant Current KCs and Capabilities

Current capabilities are compared with product characteristics to capture existing solutions and identify areas for development for future development of the assembly system and to indicate feasibility. Much of the technologies can be transferred from one aircraft program to another. This is for economic reasons. Much effort is expended on developing technologies for one aircraft program due to the long times between aircraft launches. As a result it is cost-effective to transfer technologies to comparable aircraft programs. Figure 61 shows a mid-section of the NGCW wing assembly which was used for tolerance analysis. The full wing design is still in development and the mid-section LE represents a typical worst case tolerance stack-up based on workshop discussions. The AKCs and MKCs of this section can be compared to capabilities of current wing mid-sections to identify transferable technologies which can be used to influence the system design. This comparison is shown in Figure 62. Once the relevant current capabilities are identified they are established as the baseline. The lessons learned from this baseline are then captured and used to influence RAS design. It is important to capture lessons learnt

from the baseline to avoid repeating previous errors in production. Lessons learnt is facilitated through workshop discussions with Airbus engineers and suppliers.

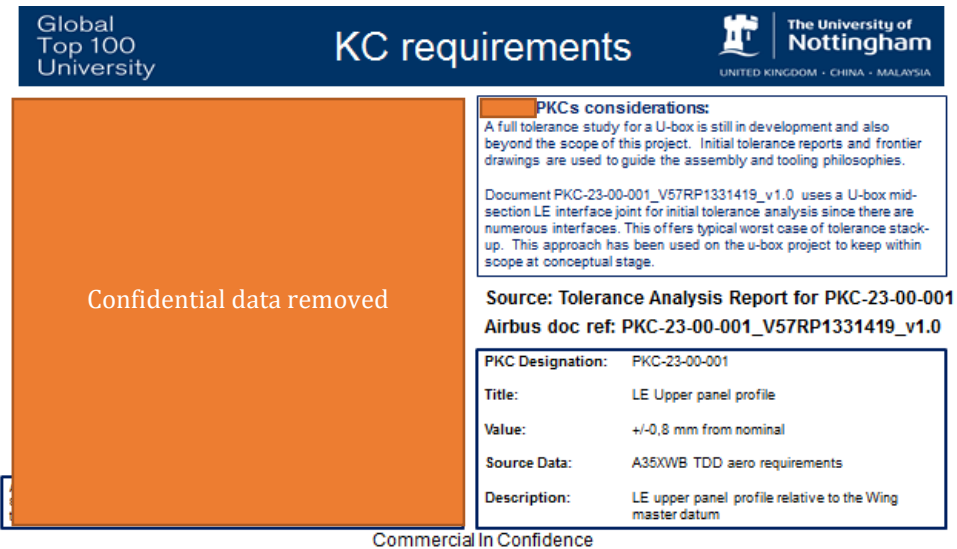


Figure 61. NGCW assembly section used for tolerance analysis (Sakota & Airbus S.A.S 2013; T. G. Jefferson & Woolley 2014b)

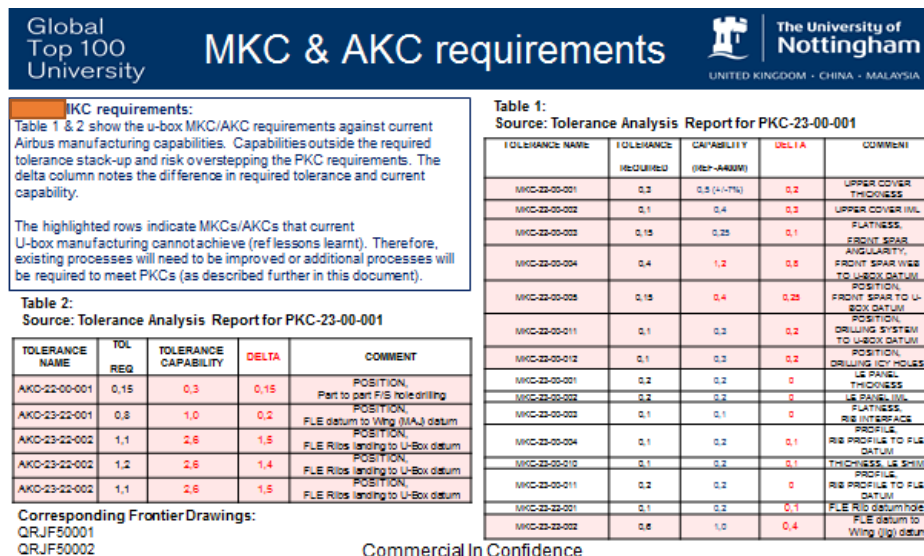


Figure 62. NGCW tolerance requirements compared with current capabilities of A400M and A350-900 (Sakota & Airbus S.A.S 2013; T. G. Jefferson & Woolley 2014b)

6.3 Customer Needs

The NGCW Customer Attributes data is organised into formal Customer Needs for mapping to constraints and FRs. The requirements of the wing and manufacturing system as well as the existing knowledge are used to influence the manufacturing system design. This stage is used to check the data for consistency and contradictions and revisited if necessary. The formal Customer Needs are then agreed with Airbus to verify the information before design begins. The needs for customisation and scalability are formed in Customer Attributes to be ultimately satisfied by a RAS. The NGCW factory requires flexible rates to match demand and customisation for future variants. These requirements are captured from various levels of engineering, design, manufacturing and management to provide as much richness as possible to ensure the customer needs are complete for translation into physical designs. Customer Needs set formal requirements that the RAS

must adhere to without limiting innovation. The design process itself can refer to the Customer Attributes for influence to solutions. The Customer Needs presented in Table 13 where reviewed by Airbus and agreed before design decomposition. Customer Needs are basic in this case because NGCW is in early stages of development and this is the first instance of the ASD.

Table 13. Formal Customer Needs

No.	Customer Needs
CN ₁	Assemble NGCW Primary Structures
CN ₂	Rate 60 capacity plus ramp up capability
CN ₃	>50% Ramp-up reduction time compared to A320
CN ₄	Capability to assemble new variants
CN ₅	Minimise factory volume
CN ₆	Minimise working at height
CN ₇	Maximise commonality
CN ₈	Maximise high-TRL 'off-the-shelf' solutions
CN ₉	Horizontal build
CN ₁₀	Incorporate lessons learnt
CN ₁₁	Incorporate R&D

6.4 Design Decomposition

Customer Needs are formalised for the NGCW aircraft and set the precedent for the ASD. The design process for the NGCW RAS is described in step-by-step fashion with accompanying rationale. The AD decomposition and mapping process for the RAS is presented with details of the activities for specifying the right levels of capacity and functionality. The same follows for the DSM construction, 3D design and reconfiguration scenarios. The NGCW aircraft is a live Airbus project and aspects relating to real-world constraints are included. The final cell designs are presented which are part of the project deliverables to Airbus stakeholders.

6.4.1 Mapping of Customer Needs to Constraints

Customer Needs are used to formulate the Constraints. For the NGCW assembly, the Input Constraints specify high-level customisation and scalability criteria so that any design solution yields a reconfigurable system. Constraints are presented in Table 14. Constraints for NGCW where drawn from Airbus-approved Customer Attributes and Needs for capacity and model change which form the basis for technical criteria for the system design. The constraints define the boundaries for system reconfigurability so that solutions embody exactly the capacity needed when needed. NGCW ASD begins with few constraints since the wing design is in the early stages and has unfixed geometry. This allows greater design freedom since there are fewer technical restrictions on solutions. However, as design progresses more constraints will be introduced which may force changes to the ASD. The knowledge capture stage captures uncertainty surrounding the wing design to mitigate this effect and influence the ASD.

Table 14. Constraints

No.	Constraints
C ₁	Assemble a minimum of 60 wing sets per month
C ₂	Ramp up >25% production rate <12 months
C ₃	Functionality to assemble all model variants
C ₄	NGCW design data at current maturity
C ₅	Current H&S
C ₆	Current certification criteria

6.4.2 Map Customer Needs and Constraints to First-Level FR

The Customer Needs and Constraints are used to define a consistent first-level FR from which the design decomposition is based. All sub-FRs and DPs must be consistent with first-level FR, Constraints and Customer Needs. The First-level FR for NGCW is presented in deconstructed format in Figure 63. It contains the operation (assembly), the product family and reference to change in production rate. These constituents of the FR make up the requirement for a RAS such that, scalability and customisation must be included in sub-FRs to maintain consistency with the FR at the first level of decomposition.

6.4.3 Map First-Level FR to First-Level DP

The Customer Needs and Constraints for NGCW assembly are characterised as FR1 so DP1 is specified to satisfy the FR. DP1 is the physical solution that completely satisfies the function expressed in FR1. FR1 states the need to assemble a part family at a variable rate. A RAS NGCW wing family satisfies this need. Figure 63 shows the constituent elements of the FR mapped to DP1.

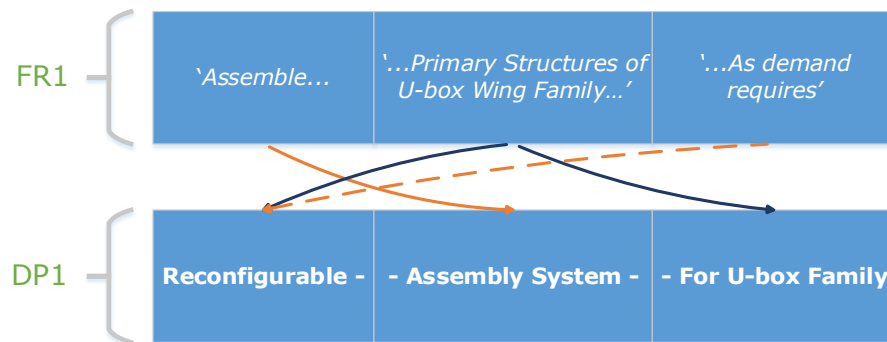


Figure 63. Constituent elements of FR1 mapped to DP1

6.4.4 Map First-Level DP to Second-Level FRs

Customisation and scalability characteristics are embodied in DP1 by translating specific Customer Needs for ramp-up and product family assembly requirements. DP1 is now decomposed into sub-functions which specifies requirements for reconfigurability in more detail in order to give exactly the capacity/functionality needed when needed.

At this stage, the design team agree a solution because there are several ways in which the sub-FRs can be expressed. The FRs for NGCW assembly were elicited by discussion and concept sketches with stakeholders in workshop sessions using designer knowledge and Customer Needs information. Captured Customer Needs were used to guide the second level FR decomposition to ensure the final design implementation meets Customer Attributes. The assembly process is defined by Airbus tolerance studies captured in Customer Needs. The major assembly processes specified by GD&T were used as the starting point for decomposition into sub-FRs because first level FR-DP specifies that these be completed as demand requires with minimum rate constraint of 60 aircraft-per-month. A major assembly process can be defined as an assembly process that achieves one or more AKC sub-assemblies as specified by GD&T (Sakota & Airbus S.A.S 2012). Major assembly processes are also influenced from the baseline and R&D lessons learnt. Of course, there are many possibilities for the order of assembly. The design practices of AD still apply such as minimum set of FRs to satisfy the higher levels and constraints. Isolating major assembly processes in this way allows functions to be satisfied by independent DPs which enables scalability and agility. Table 15 specifies the major assembly processes as requirements. The processes are then considered against Constraints for scalability and customisation to specify formal FRs for decomposition so as to design the system to be scalable from the outset.

Table 15. Major assembly processes for Airbus NGCW

Major Assembly Processes
NGCW spars drilling and machining
Assemble trailing edge components
Assemble leading edge components
Set ribs
Locate and drill upper cover
Final fasten upper cover

The major processes are specified as FRs consistent with the first-level FR and DP. Table 16 shows the major assembly processes specified as FRs which are consistent with FR1, DP1 and Constraints. Requirements for capacity and part family are specified where appropriate to give exactly the capacity/functionality needed when needed. Functions are to change rate and assemble part families. These functions will be satisfied by physical solutions. The functions of the RAS for NGCW family (DP1) are now expressed as independent sub-functions which will be satisfied by physical designs. The reconfigurability requirements are expressed in more detail at this stage. The FRs for response to demand (satisfied by scalability) and part family (satisfied by customisation) are specified at this level to be consistent with FR1 and DP1. FR11-FR17 are added to the hierarchy shown in Figure 64.

Table 16. Major assembly processes specified as functional requirements consistent with first level FR and DP

Major Assembly Processes		Second-Level FR
NGCW spars drilling and machining	FR11	Produce geometries for NGCW family at required rate
Assemble trailing edge components	FR12	Assemble trailing edge components at required rate
Assemble leading edge components	FR13	Assemble leading edge components at required rate
Set ribs	FR14	Assemble ribs to NGCW at required rate
Locate and drill upper cover	FR15	Align and drill upper cover to wing box at required rate
Equipping	FR16	Equip internal systems at required rate
Final fasten upper cover	FR17	Final fasten upper cover to wing box at required rate

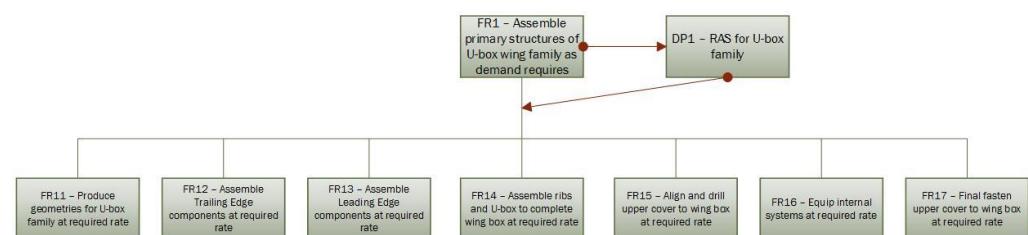


Figure 64. Mapping DP1 into independent Functional Requirements

6.4.5 Map Second-Level FRs to Second-Level DPs

Physical solutions are now conceived to satisfy the second-level FRs. Cycle time is calculated from production rate requirement to influence DP selection. Cycle time is defined as the time between when one work unit (wing) begins assembly and when the next begins (Groover 2014, p.65). The cycle time represents the maximum amount of time the longest process can take without contradicting the rate constraint. The maximum cycle time to produce one aircraft at required rate is calculated by dividing available time per month by number of aircraft per month (Equation 6.1). The cycle time is also used as part of the scalability. It is used to calculate throughput capacity with ramp-up reconfigurations.

$$\begin{aligned}
&60 \text{ aircraft per month} \\
&60 \text{ aircraft per 30 days (720 hours)} \\
&\frac{720 \text{ hours}}{60 \text{ aircraft}} = 12 \text{ hours per aircraft}
\end{aligned}
\tag{6.1}$$

This value is compared to the Customer Attributes for lessons learnt and R&D for feasibility which then guides the second-level DPs. Conceptual sketches during workshop discussions were employed to develop DPs for the NGCW RAS.

Independent cells can be reconfigured in isolation without affecting other assembly processes. This reduces the time and cost to ramp-up production because less modifications are required. A RAS is most effective with minimal coupling to allow cost-effective change in capacity or demand. Using dedicated cells for each function also means that scaling up production rates can take place simultaneously as opposed to commissioning a new fixture.

Each cell concept is considered in detail through workshop discussions both to determine technical feasibility and to employ lessons learnt knowledge. Table 17 presents the complete DPs mapped to FRs. DPs are specified as reconfigurable which captures scalability *and* customisation characteristics. This is due to FRs specifying part family production and response to demand. For instance, FR13 requires assembly of leading edge components of multiple wing products at required rate. The design solution to satisfy this function needs to be customisable (for part family) and scalable (for required rate) so is therefore expressed as Reconfigurable LE assembly cell. Figure 67 shows the second-level DPs added to the hierarchy structure and the mapping of FRs to corresponding DPs.

Table 17. Second-level FRs and DPs for NGCW RAS AD decomposition

Second-Level FR		Second-Level DP	
FR11	Produce geometries for NGCW family at required rate	DP11	Reconfigurable Machining Cell
FR12	Assemble trailing edge components at required rate	DP12	Reconfigurable TE assembly cell
FR13	Assemble leading edge components at required rate	DP13	Reconfigurable LE assembly cell
FR14	Assemble ribs to NGCW at required rate	DP14	Reconfigurable rib assembly cell
FR15	Align and drill upper cover to wing box at required rate	DP15	Reconfigurable upper cover drilling cell
FR16	Equip internal systems at required rate	DP16	Reconfigurable equipping station
FR17	Final fasten upper cover to wing box at required rate	DP17	Reconfigurable final fastening cell

6.4.6 Produce Design Matrix

A design matrix is produced to show the relationships between FRs and DPs (Figure 65). Coupling between elements is marked by a '1', decoupling is marked by '0' or left blank. For the NGCW RAS, the design is a decoupled design because of the inherent assembly sequence where machining the wing (DP11) affects downstream assembly functions (FR11-FR14). The machining cell (DP11) affects the trailing edge assembly function (FR12) because it produces the spar face MKCs onto which the trailing edge is assembled. Reconfiguring the machining cell for change such as spar geometry modification means the trailing edge assembly function may be affected.

	DP11	DP12	DP13	DP14	DP15	DP16	DP17
FR11	1						
FR12	1	1					
FR13	1		1				
FR14	1			1			
FR15	1			1	1		
FR16						1	
FR17					1		1

Figure 65. Design Matrix to show coupling between second-level FRs and DPs. Coupling between elements is marked by a '1', decoupling is marked by '0' or left blank

6.4.7 Map Second-Level DPs to Third-Level FRs

DP11-17 can now be mapped to third-level FRs. Third-level FRs were established through technical discussions in workshop sessions. FRs relating to response to demand were developed according to data gathered from lessons learnt and designer knowledge. The zigzagging process for third-level FRs is presented in Figure 68. The complete list of third-level FRs is presented in Table 18. The hierarchy of third-level FRs is presented in Figure 69. Each Second-level DP is decomposed into further sub-functions which specify reconfigurable and non-reconfigurable needs. The overall cell time is fixed by second-level FRs and so times for the third-level FRs must amount to this value. Here, third-level FRs must be consistent with higher-level requirements for scalability. To maintain consistency the design teams specify requirements to shorten cycle time. These can then be satisfied by scalable processes in third-level DP selection.

6.4.8 Map Third-Level FRs to Third-Level DPs

The mapping process was carried out in workshop sessions using data gathered from lessons learnt and designer knowledge. The complete set of third-level FRs and DPs is presented in Table 19 and in hierarchical format in Figure 70. FRs which require cycle time compression (and therefore overall cell time) are satisfied by scalable elements designed accordingly by the design team. Fixed cycle times are satisfied by non-scalable elements. This process of decomposition of FRs and DPs allows the designers to systematically design a system with the right levels of scalability and customisation.

6.4.9 Construct Supermatrix

Figure 66 shows an example design matrix for FR11-DP11. Similar design matrices are created for all the second-level FR-DPs. A supermatrix is constructed from all the design matrices to show the coupling in detail (Figure 71).

6.4.10 AD Design Decomposition Summary

AD decomposition is complete and based on Airbus needs and aspirations captured through various sources. A hierarchy is built up of FRs and corresponding DPs. The AD method specifies functional architecture for a RAS and corresponding physical system to satisfy functions. The hierarchical approach allows scalability and customisation to specifying exactly the capacity needed when needed by decomposing high-level requirements into sub-functions and corresponding physical elements. Only certain parts of the system need to be changed to have the capability to increase capacity. Systematic decomposition of the system allows the designer to specify which subsystems need to be designed to be changeable. However, AD does not define a physical architecture – this is achieved using DSMs, described in next section.

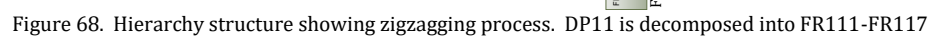


Table 18. Third-level FRs for NGCW RAS

Second level FR		Third-Level FR
FR11	FR111	Deliver wingbox for various geometries
	FR112	Hold flight surface PKC for multiple geometries
	FR113	Machine multiple spar cap and spar face geometries
	FR114	Vary the machining rate for ramp-up
	FR115	Drill spar faces for part family
	FR116	Vary drilling rate for ramp-up
	FR117	Transport different wingboxes to next cell
FR12	FR121	Deliver machined wingbox variations from previous cell
	FR122	Hold wingbox variations in ergonomic position
	FR123	Deliver TE components in ergonomic position
	FR124	Align, seal and fasten components to U-box at required rate
	FR125	Deliver wingbox assemblies to next cell
FR13	FR131	Deliver machined U-box variations from previous cell
	FR132	Hold wingbox variations in ergonomic position
	FR133	Deliver LE components in ergonomic position
	FR134	Align, seal and fasten components to wingbox
	FR135	Deliver wingbox assemblies to next cell
	FR141	Deliver and load wingbox family from previous cell
	FR142	Constrain PKCs for wingbox family while assembling ribs
FR14	FR143	Constrain hinge line KCs for wingbox family while ribs are drilled and fastened
	FR144	Constrain leading edge KCs for wingbox family while ribs are drilled and fastened
	FR145	Deliver ribs for assembly
	FR146	Position and clamp ribs to rib posts and rib feet at required rate
	FR147	Assemble ribs at required rate
	FR148	Deliver wing-box family to next cell
	FR151	Deliver assembled wingbox family from previous process
	FR152	support wing box structures during drilling
FR15	FR153	Deliver upper cover
	FR154	Locate upper cover to wing-box
	FR155	drill and slave fasten cover to wing-box
	FR156	Drill full size cover to spar and cover to rib feet as demand requires
	FR157	remove cover after drilling
	FR158	transport cover to next process
	FR159	transport wing-box to next process
FR16	FR161	Deliver wingbox variations from previous cell
	FR162	Hold wingbox variations in ergonomic position
	FR163	Fit all systems at required rate
	FR164	Transport equipped wing-box to next process
	FR171	Deliver equipped wingbox
FR17	FR172	Apply sealant
	FR173	Relocate cover
	FR174	Final Fasten at required rate

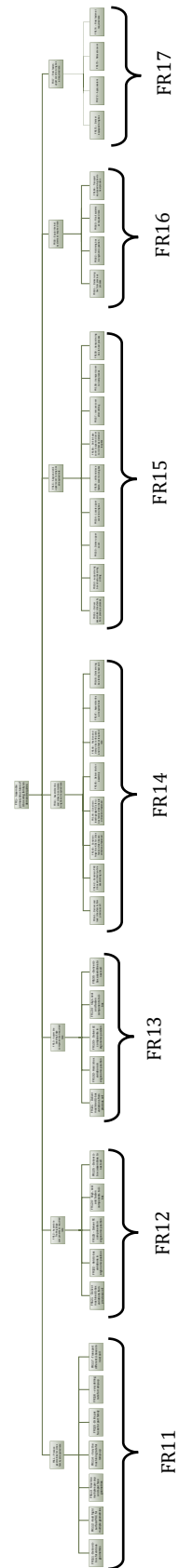


Figure 69. Hierarchy of FRs decomposed to third level

Table 19. Third-level FRs and corresponding third-level DPs

Third Level FR	Third-Level DP
FR111 Deliver U-box for various geometries	DP111 Crane and lifting fixture common to all geometries
FR112 Hold flight surface PKC for multiple geometries	DP112 Fixture customisable for different geometries
FR113 Machine multiple spar cap and spar face geometries	DP113 Customisable machining system
FR114 Vary the machining rate for ramp-up	DP114 Modular machining system
FR115 Drill spar faces for part family	DP115 Customisable drilling system
FR116 Vary drilling rate for ramp-up	DP116 Modular drilling system
FR117 Transport different U-boxes to next cell	DP117 AGV common to all geometries
FR121 Deliver machined U-box variations from previous cell	DP121 AGV
FR122 Hold U-box variations in ergonomic position	DP122 Locators common to all geometries
FR123 Deliver TE components in ergonomic position	DP123 TE transport AGV
FR124 Align, seal and fasten components to U-box at required rate	DP124 Trained operators and toolsets
FR125 Deliver U-box assemblies to next cell	DP125 AGV
FR131 Deliver machined U-box variations from previous cell	DP131 AGV
FR132 Hold U-box variations in ergonomic position	DP132 Locators common to all geometries
FR133 Deliver LE components in ergonomic position	DP133 LE transport AGV
FR134 Align, seal and fasten components to U-box	DP134 Trained operators and toolsets
FR135 Deliver U-box assemblies to next cell	DP135 AGV
FR141 Deliver and load U-box family from previous cell	DP141 AGV and loading fixture common to all geometries
FR142 Constrain PKCs for U-box family while assembling ribs	DP142 Common skin support holder
FR143 Constrain hinge line KCs for U-box family while ribs are drilled and fastened	DP143 Modular hinge line fixturing system
FR144 Constrain leading edge KCs for u-box family while ribs are drilled and fastened	DP144 Modular leading edge location system
FR145 Deliver ribs for assembly	DP145 Rib AGV delivery system
FR146 Position and clamp ribs to rib posts and rib feet at required rate	DP146 Scalable rib position and clamping module
FR147 Assemble ribs at required rate	DP147 Scalable drilling, sealing and fastening module
FR148 Deliver wing-box family to next cell	DP148 Transport AGV
FR151 Deliver assembled U-box family from previous process	DP151 AGV common to all geometries
FR152 support wing box structures during drilling	DP152 Skin support common to all geometries
FR153 Deliver upper cover	DP153 Crane and lifting fixture common to all geometries
FR154 Locate upper cover to wing-box	DP154 Pin and slot mechanism
FR155 drill and slave fasten cover to wing-box	DP155 Single-sided drill & slave module
FR156 Drill full size cover to spar and cover to rib feet as demand requires	DP156 Duplicable drilling module
FR157 remove cover after drilling	DP157 Crane and lifting fixture common to all geometries
FR158 transport cover to next process	DP158 Crane and lifting fixture common to all geometries
FR159 transport wing-box to next process	DP159 AGV
FR161 Deliver wingbox variations from previous cell	DP161 AGV
FR162 Hold wingbox variations in ergonomic position	DP162 Rotating Fixture
FR163 Fit all systems at required rate	DP163 Manual fitting
FR164 Transport equipped wing-box to next process	DP164 AGV
FR171 Deliver equipped wingbox	DP171 AGV
FR172 Apply sealant	DP172 Trained operators with toolsets
FR173 Relocate cover	DP173 Crane and fixture with operators
FR174 Final Fasten at required rate	DP174 Trained operators with toolsets

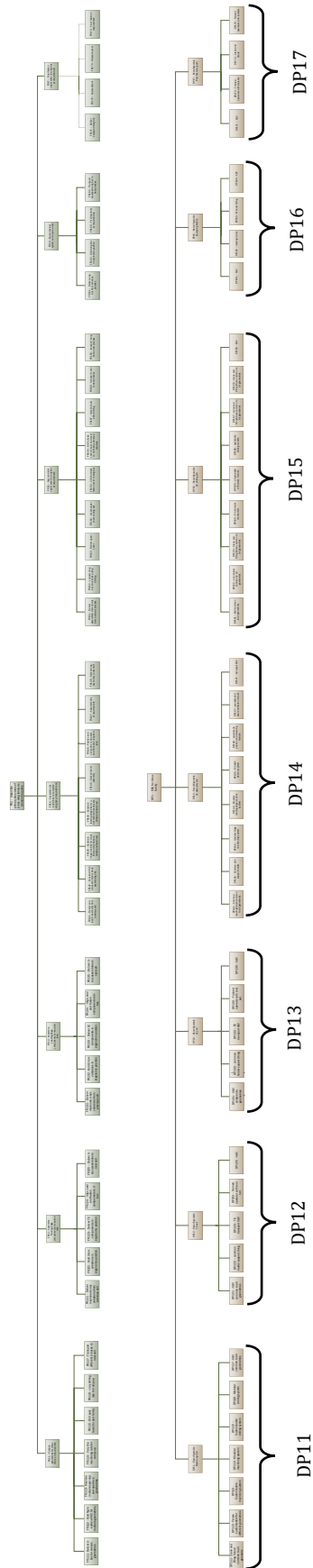


Figure 70. Hierarchy of FRs and DPs (zigzagging not shown)

			DP1																															
			DP11					DP12					DP13					DP14	DP15					DP16		DP17								
			DP111	DP112	DP113	DP114	DP115	DP116	DP121	DP122	DP123	DP124	DP125	DP131	DP132	DP133	DP134	DP135	DP136	DP137	DP141	DP142	DP151	DP152	DP153	DP154	DP155	DP161	DP162	DP163	DP171	DP172	DP173	
FR1	FR11	FR111	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR112	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR113	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR114	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR115	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR116	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	FR12	FR121	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR122	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR123	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR124	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR125	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	FR13	FR131	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR132	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR133	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR135	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0		
		FR137	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0		
	FR14	FR141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0		
		FR142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		
	FR15	FR151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0		
		FR152	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0		
		FR153	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0		
		FR154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0		
		FR155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0		
	FR16	FR161	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	
		FR162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	
		FR163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
	FR17	FR171	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
		FR172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	
		FR173	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
FR174		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		

Figure 71. Supermatrix of lower level FRs and DPs

6.5 DSM Modelling

This section details the DSM construction process. The DSMs are constructed into Product, Process and System (PPS) domains for design integration and system representation. The PPS framework is used to show the relationships inside each domain as well as the relationships between domains. Relationships are shown for single domains such as the physical connectivity of the product elements. Relationships between domains highlight interactions which influence the design, such as what system elements use which processes which affects the factory layout. This information is later used for reconfigurations to calculate the changes to the system for a given reconfiguration. The translation of DPs into DSMs is explained using examples before presenting each cell design in detail with its associated DSM. The final factory DSM of the entire system design is presented also.

6.5.1 System DSM

The designer team used previous experience and Customer Attributes data to devise assembly system components consisting of the DPs. Feasibility studies were carried out during this process to verify the tooling designs for production. Figure 72 presents additional decomposition to fourth-level FRs and DPs which was required to observe a feasible design for cell 4. Missing or incomplete elements may lead to redesign or modification in commissioning phases. In order to construct the DSMs so they capture all the necessary information a specific process for creating DSMs is prescribed. Designer knowledge is needed to accurately construct DSMs (Eppinger & Browning 2012, p.23). System interactions for NGCW RAS are modelling by the designer using existing knowledge

and in reference to the design matrix which shows design couplings. Figure 73 presents the completed system DSM for NGCW RAS.

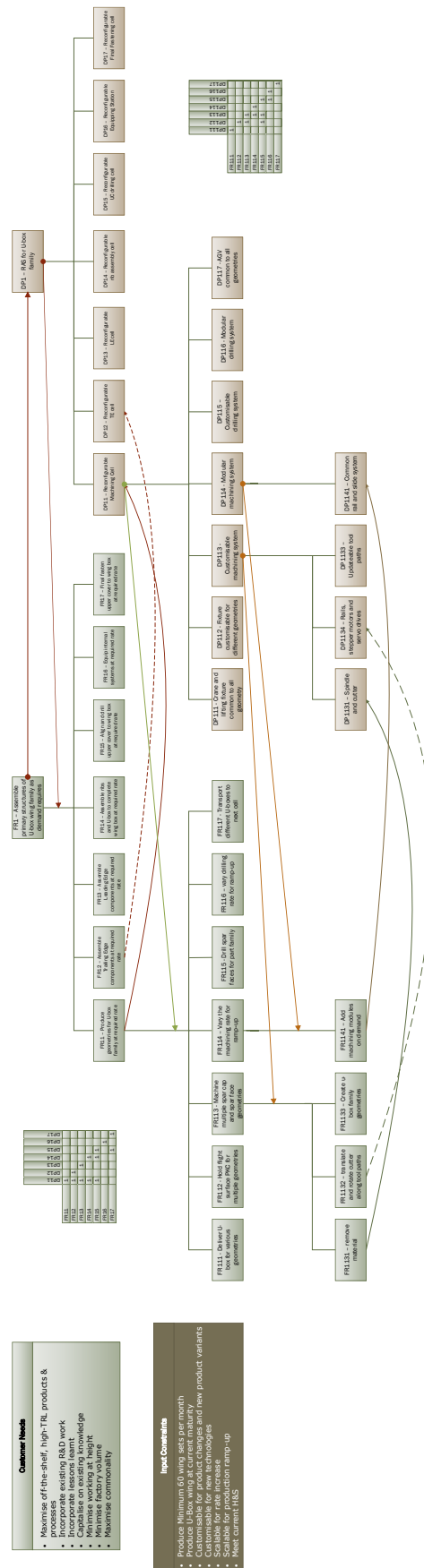


Figure 72. AD decomposition of fourth-level FRs and DPs

		39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
Crane system	39																									
AGVs for U-box	40																									
U-box Fixture system	41																									
Automated measurement system	42																									
Milling machine	43																									
Cell 1 Robot	44																									
Drilling end-effector	45																									
Laser-alignment system	46																									
Cell 2 Fixture	47																									
Cell 2 Operators	48																									
AGV hinge ribs	49																									
Cell 3 Fixture	50																									
Cell 3 operators	51																									
AGV D-noses	52																									
Cell 4 Fixture	53																									
Robot pair	54																									
Tooling frame	55																									
Position & clamp module	56																									
Drill & fasten module	57																									
Cell 5 Fixture	58																									
Flex-track	59																									
Cell 6 Fixture	60																									
Lifting frame	61																									
Cleaning equipment	62																									
Cell 6 Operators	63																									

Figure 73. Completed System DSM for NGCW RAS

6.5.1.1 Product DSM

As with the system DSM, a degree of designer input is required to develop the remaining DSMs. The NGCW KC features are constructed into a DSM to show where dependencies lie and to highlight interactions. Figure 74 shows a completed example of the product features created in cell 1.

		1	2	3	4	5
Lower Cover PKC	1					
Spar face MKC (LE & TE)	2					
Spar cap MKC (Underside)	3					
Spar cap MKC (Upperside)	4					
Bracketry holes (LE & TE)	5					

Figure 74. Cell 1 Product DSM

6.5.1.2 Cell 1 Process DSM

The process DSM requires the most amount of designer input. The process DSM is created from the product and system DSMs as well as the AD decomposition and cell layout. It is also influenced by the system and product DSMs. The process DSM contains all the steps to assemble the wing KCs. The process DSM represents the assembly activities and so is only composed of process interaction types. A portion of the process DSM for NGCW assembly is shown in Figure 75. There are no conditional processes for NGCW assembly so sequential, parallel and coupled activities are represented using the same marking. Sequential activities are lower-triangular and upper-triangular markers represent coupled processes where feedback loops are needed e.g. for metrology feedback to actuators for positioning.

		A	B	C	D	E	F	G	H	I
Load U-box onto datum locators and PKC form boards	A									
Install spreader clamps and claim lower cover PKC	B									
Clamp spar faces	C									
Check spar faces	D									
Machine spar caps (Upperside)	E									
Machine spar caps (Underside)	F									
Machine spar faces	G									
Laser-align drill tool	H									
Drill hole patterns	I									

Figure 75. Process DSM for cell 1

6.5.1.3 Factory PPS DSM

The complete PPS DSM model with MDM is presented in Figure 76. Elements are numbered to help the designer specify the interactions. The DSMs and interactions between domains inform the physical layout of the cell and specific sequence of operations. Figure 76 shows the complete DSMs for NGCW assembly with MDM between domains. The PPS DSM is later used for highlighting changes in the system caused by reconfigurations once the 3D Design is complete.

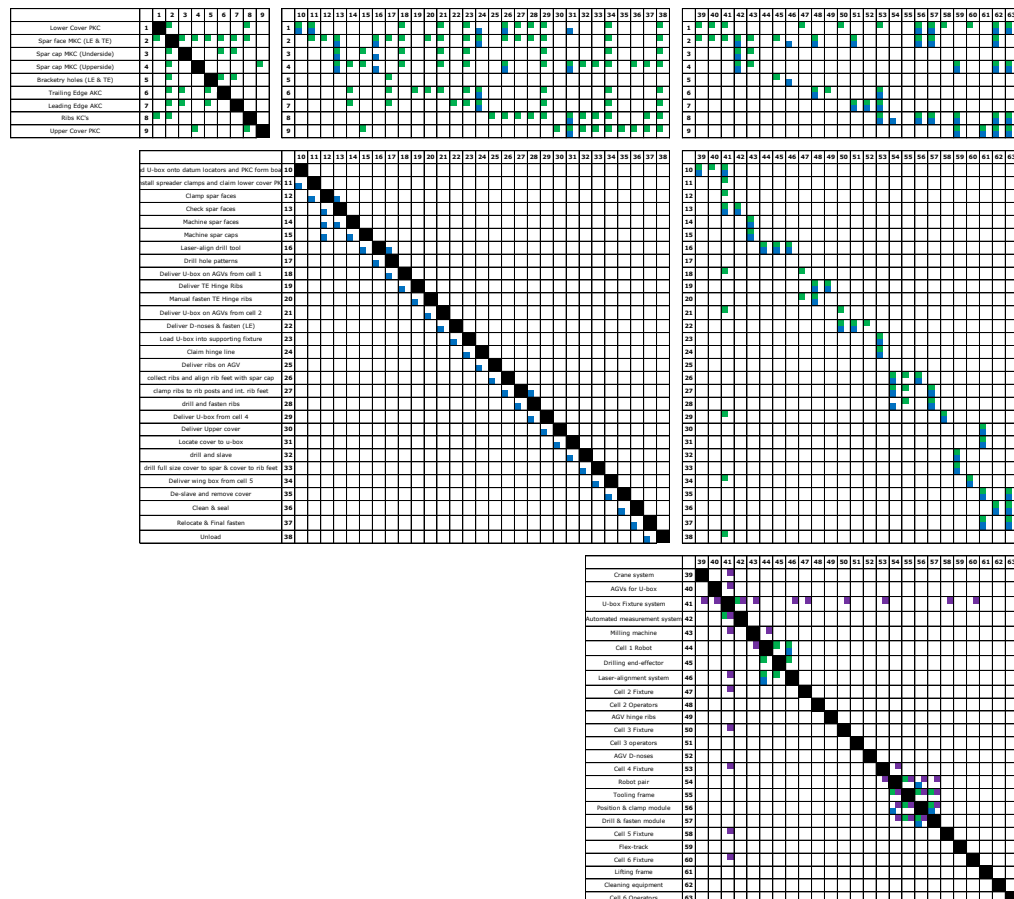


Figure 76. Factory DSM of Product, Process and System for NGCW RAS

6.6 Map DSMs to 3D CAD

The DSMs are used for 3D design of assembly cells for NGCW assembly and are described in this section. How the DSMs are used is discussed where appropriate and the working principles and engineering rationale associated with the project are also described for each cell. Supporting capabilities and rates are also estimated according to project needs. Cells were designed with automation and tooling designers in workshops then agreed with stakeholders. The DSMs provided much needed guidance to designers and reduced the time to search for solutions. Also reducing the number of redesigns because of clashes was less because of the modelling interactions aiding the designer's design process. The approach capitalises on designer knowledge by providing more design information at the beginning and reduces the amount of unknowns during design.

A full ASD is now modelled and complete with interactions necessary for detailed design. The DSMs are used to guide the detailed design of the cells. Designers use the DSM interactions to produce 3D geometry of the elements and the assembly processes (Figure 77).

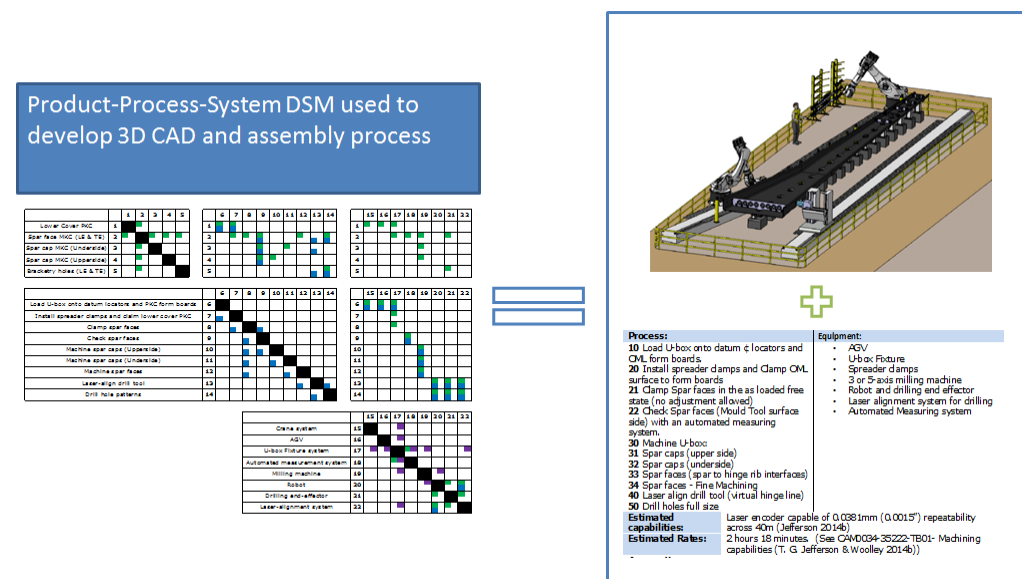


Figure 77. PPS-DSMs are used by designers to develop the 3D CAD and processes for wing assembly

Knowing the interactions sets the physical bounds on the system and the designers can construct geometry according to a prescriptive structure based on the AD architecture. Observing specified interactions, DSMs form the technical boundaries for the detail design and guide the design process. Spatial proximity interactions are identified which promotes communication. The PPS DSM is embodied in the 3D physical design and associated processes, derived from decoupled system architecture specifying the necessary levels of scalability and customisation for Customer Needs. What was a previously ad-hoc design method is now guided by parameters which optimise the search for a satisfactory solution. Human design process (creativity) is unrestricted and still allows novelty. Design is carried out in pragmatic way with regard to DSM interactions. Because of the early stages of the design, working assumptions are included. Some extra work into feasibility was carried out to justify some of the designs. The final 3D factory corresponds to the factory DSM and can be used to simulate changes and reconfigurations.

6.6.1.1 Cell 1 NGCW Drilling and Machining

Cell 1 is the physical realisation of DP11 to satisfy FR11 – ‘Produce Wingbox Geometries for Wingbox Family at Required Rate’. Figure 78 presents the PPS-DSM used to carry out the detailed design of the cell. Highlighting the spatial proximity interactions in this cell is particularly important for avoiding clashes between the wing, fixture tooling and the robot with end effector given the complex geometry of the wing fixture and robot. The visual representation allows the design team to develop both solutions simultaneously ensuring compatibility. The interactions highlighted between process and system are used to inform the control sequences of automation equipment.

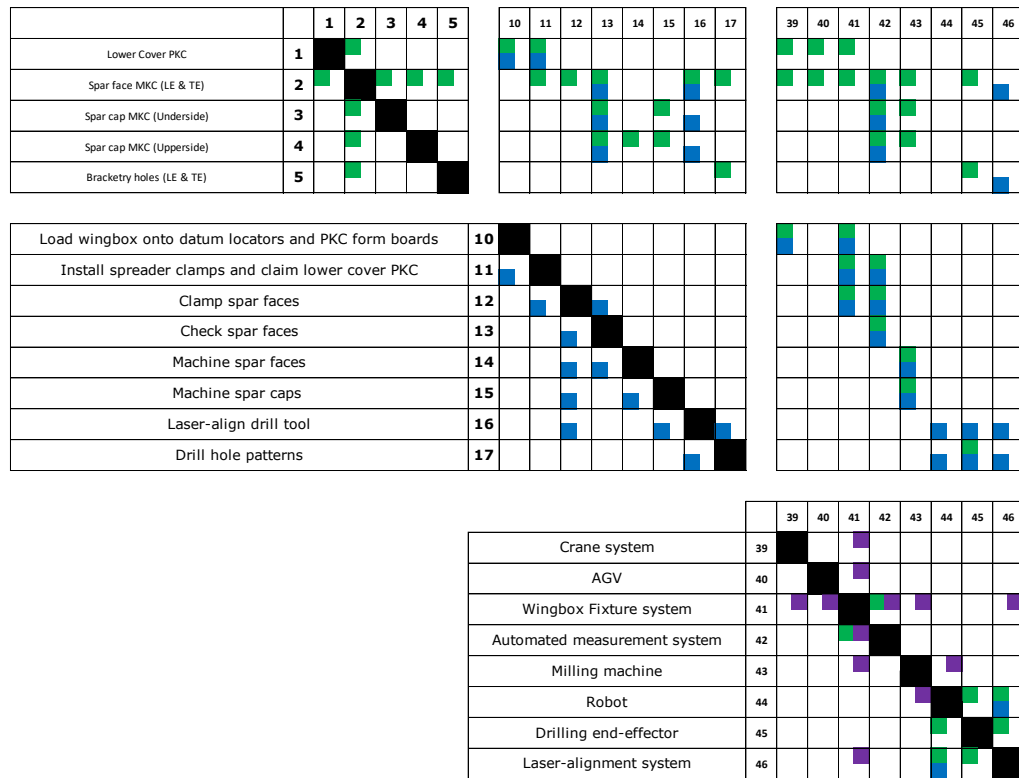


Figure 78. MDM of cell 1 Product, Process and System DSMs

Cell 1 (Figure 79) receives a cured wingbox via AGV or crane and locates the skin onto profile PKC tooling. Spreader clamps hold the skin against the tooling and also provide stability for the spars when machining, Figure 79 (right). The spreader clamps also provide opportunity to manipulate the spar faces depending on Condition of Supply (CoS). Then the spar faces and spar caps are machined. Machining capability and rate is covered and machining accuracies benchmarked. After machining, the drilling takes place and uses laser metrology to achieve hole-to-hole assembly. The additional work for machining and drilling is detailed in technical reports (Jefferson 2014b; Woolley & Jefferson 2014a).

Table 20. Cell 1 Processes

Process:	Equipment:
10 Load wingbox onto datum & locators and OML form boards. 20 Install spreader clamps and Clamp OML surface to form boards 21 Clamp Spar faces in the as loaded free state (no adjustment allowed)	- AGV - Wingbox Fixture - Spreader clamps 3 or 5-axis milling machine - Robot and drilling end effector - Laser alignment system for drilling - Automated Measuring system

22 Check Spar faces (Mould Tool surface side) with an automated measuring system. 30 Machine U-box: 31 Spar caps (upper side) 32 Spar caps (underside) 33 Spar faces (spar to hinge rib interfaces) 34 Spar faces - Fine Machining 40 Laser align drill tool (virtual hinge line) 50 Drill holes full size	
Estimated capabilities:	Laser encoder capable of 0.0381mm (0.0015") repeatability across 40m (Jefferson 2014b)
Estimated Rates:	2 hours 18 minutes. (See CAM0034-35222-TB01- Machining capabilities (T. G. Jefferson & Woolley 2014a))
Assumptions: • The rate to machine one u-box is approximately 2 hours 18 minutes presented in Machining capabilities (T. G. Jefferson & Woolley 2014a). Note this is machining time only. Total time believed to be achievable in 12 hours. The process is scalable i.e. if cycle time cannot be met with one machine, extras can be added relatively easily. • Machining accuracies can be found in Machining Accuracies Benchmark (Jefferson 2014a). Renishaw produce a laser encoder capable of 0.0381mm (0.0015") repeatability across a 40m X-axis gantry (Renishaw plc. 2013). This technology is similar to the concept employed in cell 1 for accurate milling and drilling of the spar. • Overall datum structure of the build is yet to be determined and should be high priority for future work • Features for location are yet to be determined. This build philosophy assumes there will be location points at root and tip. The final location features may be moulded hemispheres, pin and slot, tooling lugs, existing topology or a combination of. • Lower cover PKC can be claimed on tooling • Cell will be enclosed and comply with all health and safety requirements • Dust extraction and cleaning will be done in cell • Spreader clamp concept can potentially be used to adjust spars but the geometry must be captured and returned to in cell 4. Machining Accuracies Benchmark (Jefferson 2014a). Ramifications of adjusting the spars is still to be fully understood (Woolley & Jefferson 2014b) • Machining in-house is not current practice at Airbus and presents logistical challenges • Integrated rib feet are assumed to be positioned correctly for subsequent assembly. Misaligned rib feet will require a solution similar to MTF hinge rib build philosophy which will involve measuring and machining • The laser system may position the end effector relative to the wing or the fixture which will require further investigation.	

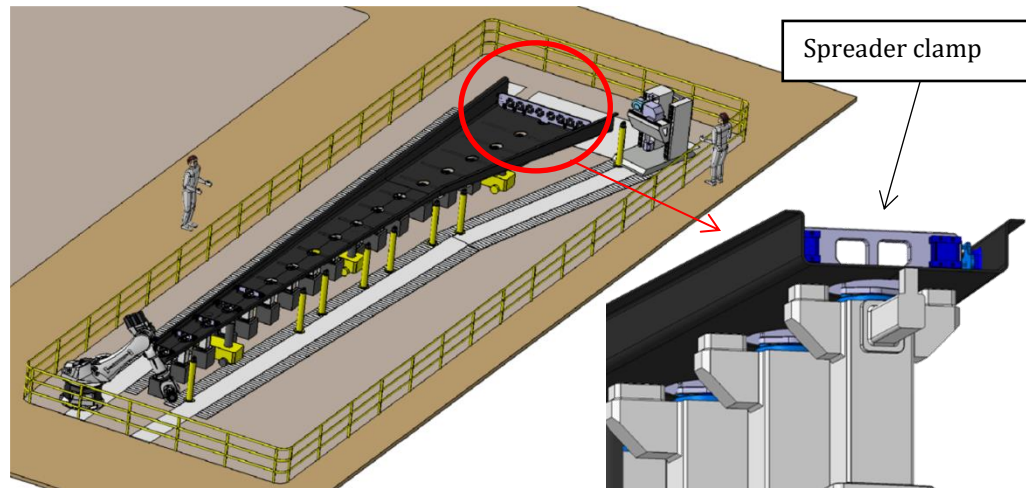


Figure 79. Cell 1 - wingbox drilling and machining, (right) close up of the support jig and spreader clamp inserts.

6.6.1.2 Machining

A custom machine tool is proposed because of the requirement for high accuracy. The interfaces directly impact upper cover profile and hinge line tolerances which are PKC requirements. It is critical that the mechanical loop remains as short as possible to reduce positional error. The short rails of this 5-axis machine concept provide minimum linear movement to reduce machining variation as much as possible, shown in Figure 80. A 2D scheme shows machining interfaces (Figure 80 inset). The calculations for machining rates are based on a wing-box case study (Sandvik AB 2014c).

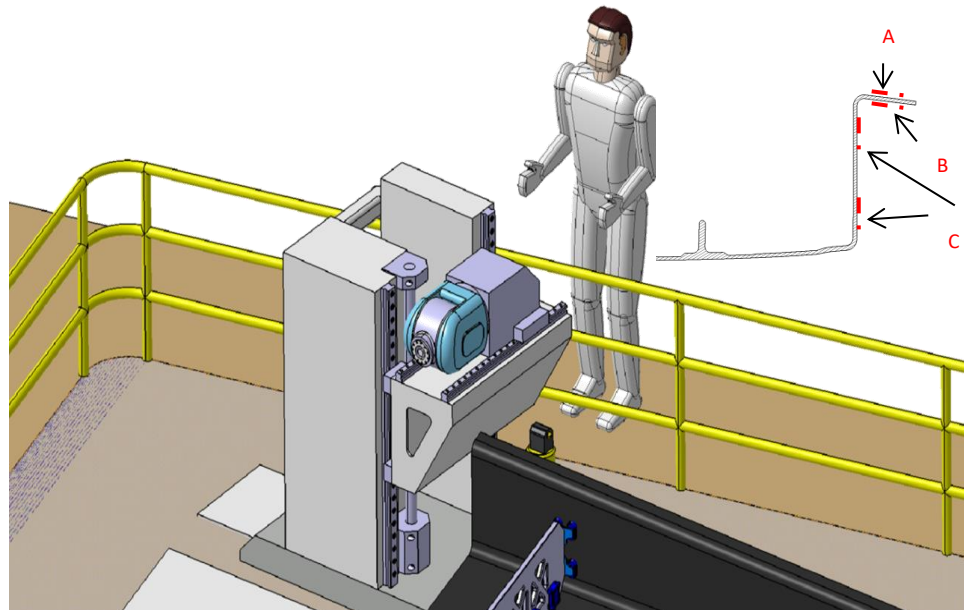


Figure 80. 5-axis machine to machine spars faces and spar caps. Inset top right: U-box interfaces to be machined assuming sacrificial pads. (A) spar cap to upper cover (B) spar cap to hinge rib or D-nose interface (C) spar face to hinge rib or D-nose

6.6.1.3 Drilling

The spar drilling operations are carried out post-machining. The drilling end effector uses high-accuracy linear rails to achieve the necessary local accuracy required for hole-to-hole assembly. The end effector is positioned using a laser and four-quadrant diode to achieve the required global accuracy (Fan & Chen 2000).

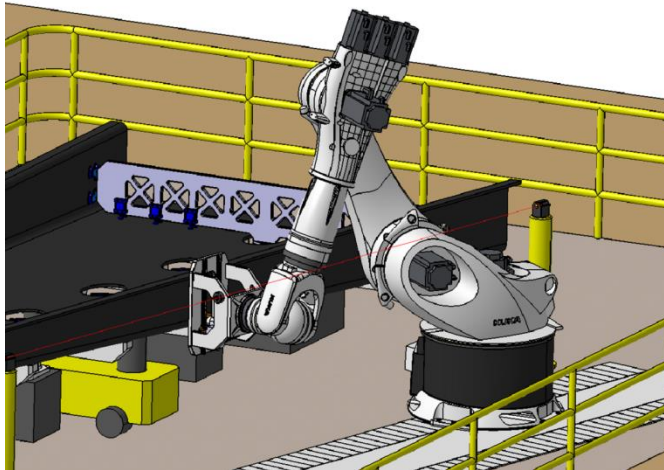


Figure 81. Drilling concept. Robot end effector has high local accuracy and laser positions end effector to global tolerance

6.6.1.4 Machining Rate

Machining of one spar cap is considered to indicate machining rates. The spar caps are the largest surface area to machine and therefore likely to be the longest process. If the sum total of the machining processes exceeds the cycle time then extra machines will be required to achieve rate. Spar cap machining will require the largest percentage of cycle time and so provides a reasonable notion of machining the wingbox within rate cycle time.

6.6.1.4.1 Assumptions

The machining depth is assumed to be 0.5mm as this is the maximum depth of a finishing cut in a single pass according to Sandvik Coromant data. Roughing cuts are quicker because of higher feed speed and greater depth of cut (Sandvik AB 2014c). A 100mm cutter (Sandvik AB 2014a) is specified arbitrarily since the aim is to calculate machining rate. Cutter selection is based on the Sandvik Coromant case study which uses a 32mm cutter. The actual cutter specification for u-box machining is dependent on the final requirements of the wingbox and may differ from the one in this case study.

6.6.1.4.2 Feeds and Speeds

Feeds and speeds data is based on a Sandvik Coromant composite wing box machining application (Sandvik AB 2014c). An excerpt is shown in Figure 82. Formulas are taken from Sandvik Coromant Milling Formulas Handbook (Sandvik AB 2014b).

Wing box

Surface machining of carbon fibre

Facts and demands

- Primary structure carbon fibre
- Minimal splintering of fibres and delamination
- Good surface finish and dimensions

Solutions

- CoroMill Century with PCD inserts
- Cutter: R590-04C3-11M
- Inserts: R590-1105H-PS2-NL CD10

Cutting data

- Cutting speed: 300m/min
- Fz: Roughing: 0.16 / Finishing: 0.1mm/tooth
- Ap: Roughing: 2.5mm / Finishing: 0.5mm



CoroMill Century

Figure 82. Excerpt from Sandvik Coromant composite wing box machining application. Cutting data is used to calculate material removal rate (Sandvik AB 2014c)

$v_c = \frac{D_{cap} \times \pi \times n}{1000}$ Cutting speed (v_c) (m/min)	$n = \frac{v_c \times 1000}{\pi \times D_{cap}}$ Spindle speed (n) (rpm)
$f_z = \frac{v_f}{n \times z_c}$ Feed per tooth (f_z) (mm)	$Q = \frac{a_p \times a_e \times v_f}{1000}$ Metal removal rate (Q) (cm³/min)
$v_f = f_z \times n \times z_c$ Table feed or feed speed (v_f) (mm/min)	

Figure 83. Formulas used in calculation of removal rate (Sandvik AB 2014b)

6.6.1.4.3 Wingbox Spar Cap Machining Rate

Cutter Diameter = 100mm (Sandvik AB 2014a)

$v_c = 300$ metres/min

$D_{cap} = 100$ mm

$f_z = 0.1$ mm/tooth

$z_c = 9$

$a_p = 0.5$ mm

$a_e = 100$ mm

$S_v =$ Spar cap volume

$R =$ Machining time

Spindle Speed (n) is calculated from empirical data consisting of Cutting Speed (v_c) and Cutter Diameter (D_{cap}) sourced from Sandvik Coromant data (*op. cit.*).

$$n = \frac{v_c \times 1000}{\pi \times D_{cap}}$$

$$n = \frac{300 \text{ m/min} \times 1000}{\pi \times 100 \text{ mm}} \quad (6.2)$$

$$\mathbf{n = 955 \text{ rpm}}$$

Feed speed (v_f) is calculated as follows using Spindle Speed, Feed per Tooth (f_z) and Number of Teeth (z_c).

$$v_f = f_z \times n \times z_c$$

$$v_f = 0.1 \text{ mm/tooth} \times 955 \text{ rpm} \times 9 \quad (6.3)$$

$$\mathbf{v_f = 859.5 \text{ mm/min}}$$

Material Removal rate is calculated from Feed Speed, Depth of Cut (a_p) and Working engagement (a_e).

$$Q = \frac{a_p \times a_e \times v_f}{1000}$$

$$Q = \frac{0.5mm \times 100mm \times 859.5mm/min}{1000} \quad (6.4)$$

$$Q = 43cm^3/min$$

Now, volume of spar cap material to be removed is calculated. These values are based on the NGCW composite wing geometry.

$$S_v = 15 \text{ metre length} \times 0.13 \text{ metre width}$$

$$S_v = 1.95m^2$$

$$S_v = 1.95m^2 \times 0.5mm \text{ cut depth } (0.0005m) \quad (6.5)$$

$$S_v = 0.000975m^3$$

$$S_v = 975cm^3$$

Spar cap volume divided by material volume removal per minute gives time needed to machine one spar cap.

$$R = \frac{975cm^3}{43cm^3/min}$$

$$R = 23mins \quad (6.6)$$

Multiplying this value by two gives the time to machine two spar caps assuming sequential machining. Using the methodology, the system is design as such so that adding an extra machining system to run in parallel allows a machining time of 23 minutes. Machining systems can be added beyond this to reduce machining time further.

Time to machine 0.5mm of one spar cap= 23mins

Time to machine 0.5mm of two spar caps = 46mins

6.6.1.4.4 Rate 60 Considerations

Machining time for one spar is estimated to be 23 minutes at 0.5mm cut depth. This represents around 3% of a 12 hour cycle time.

$$60 \text{ aircraft per month}$$

$$60 \text{ aircraft per 30 days (720 hours)}$$

$$\frac{720 \text{ hours}}{60 \text{ aircraft}} = 12 \text{ hours per aircraft} \quad (6.7)$$

Therefore, the production line should produce 1 aircraft every 12 hours (12 hour cycle time).

Machining time as % of cycle time

$$= \frac{23 \text{ minutes (time to machine one spar)}}{720 \text{ minutes (12 hours cycle time} \times 60)} \quad (6.8)$$

Machining time as % of cycle time = 3.2%

Total machining time

$$= (2 \times \text{spar caps}) + (2 \times \text{spar cap undersides}) \\ + (2 \times \text{spar faces})$$

$$\text{Total machining time} = 19\% \text{ of cycle time} \quad (6.9)$$

$$\text{Total machining time} = 138 \text{ minutes}$$

Total machining time = 2 hours 18 minutes

Assuming:

- 24 hour labour utilisation – no stoppages
- Two production lines – Port & starboard wing build, 1 mirror and 1 master
- Machining process only – no prep, cleaning, setup, etc.
- Spar cap machining is longest process i.e. worst case
- All machining times are equal
- Constant feed rate
- Wing-box geometry tool path is assumed to be achievable

6.6.1.4.5 Conclusions

Wingbox machining is feasible at rate 60 with total machining time of around 2 hours, provided that feeds and speeds are similar to existing composite wing box machining and cut depth is kept to a maximum of 0.5mm. Depths greater than 0.5mm will require more than one pass of the cutter. Each additional cutter pass increases machining time by approximately 23 minutes (using stated feeds and speeds). If total machining time exceeds the cycle time then extra machines will be required to achieve rate. AD specifies a decoupled architecture for wingbox machining and so additional machines can be added independently to increase production rate.

6.6.1.5 Cell 2

Cell 2 and 3 share a similar design for assembly of TE and LE ribs, so the DSMs are similar. The DSMs have minimal interactions (Figure 84). This is due to the AD decomposition process which promotes independent design which has led to fewer interactions i.e. coupled design. The result is a simple fixturing and assembly process which can be scaled relatively easily by adding labour to shorten cycle time.

The wingbox is transferred from cell 1 by AGVs that manoeuvres under the fixture that supports the wingbox, Figure 85. Hinge ribs are manually assembled to the spars, if hole-to-hole is not achievable then the holes can be opened up to full size before fastening. Fastening operations can be manual for low rates and automated for future high rates. Bracketry should arrive on carriages that permit quick assembly. The logistics of this system is an important area for consideration in the next phase. The assembly process and assumptions are presented in Table 21.

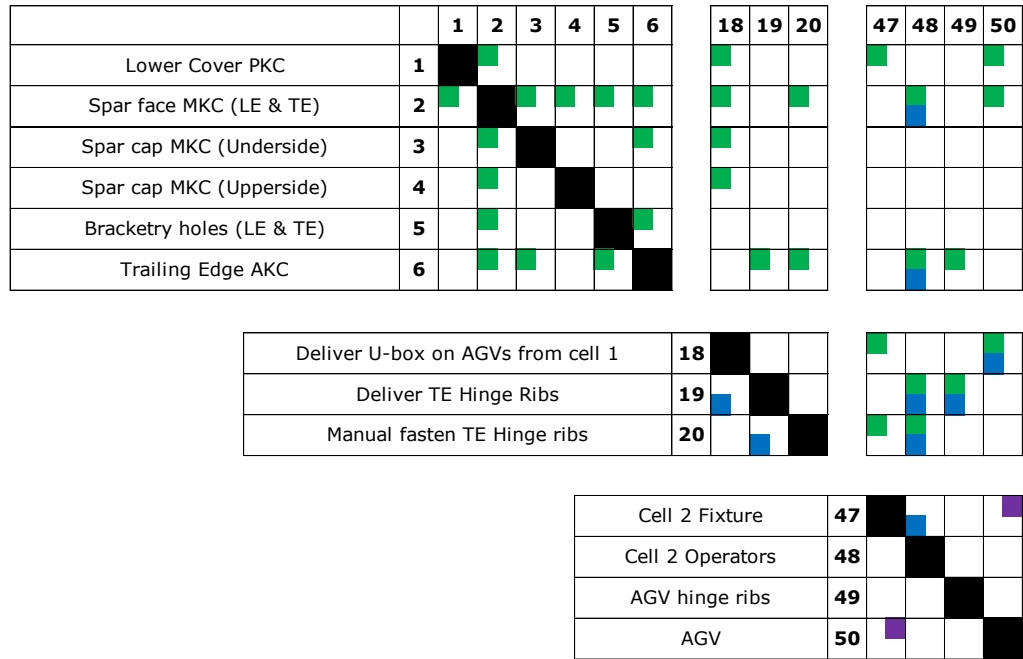


Figure 84. Cell 2 PPS DSM

Table 21. Cell 2 Process

Process:		Equipment:
10 Deliver U-box on AGVs from cell 1 20 Deliver TE hinge ribs 30 Manually fasten TE hinge ribs (part-to-part)		• AGVs for U-box • Fixture • AGVs for hinge ribs
Estimated capabilities:	Assembly should be hole-to-hole, however if hole-to-hole is not possible then these cells can be used to facilitate additional drilling processes to produce holes full size (part-to-part)	
Estimated Rates:	• 12 hour cycle time (1.5 shifts) - function of no. of operators and no. of holes • Automation is a possibility for high rate requirements	
Assumptions: • High-precision machining in cell 1 will achieve part to part assembly • Hinge rib components can be manually handled • All components are accessible at nominal working height • Wingbox is rigid enough to support the additional weight of the added componentry • Manual workers have enough room to operate to meet rate even when at saturation		

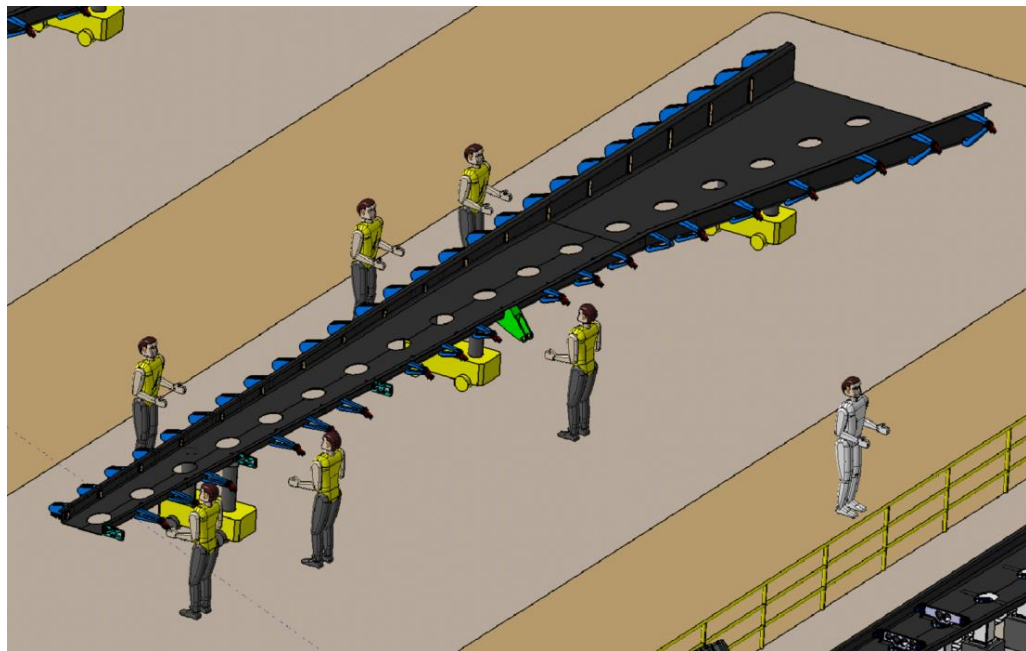


Figure 85. Cell 2 - parts are assembled to u-box hole-to-hole, reflected in the simple cell design.

6.6.1.6 Cell 3

The wingbox is transferred from cell 2 by AGVs that manoeuvres under the fixture that supports the wingbox, the same design as cell 2 (Figure 85). The DSM is presented in Figure 86 and the process is presented in Table 22. D noses are manually assembled to the spars, if hole-to-hole is not achievable then the holes can be opened up to full size before fastening. Fastening operations can be manual for low rates and automated for future high rates. Components should arrive on carriages that permit quick assembly.

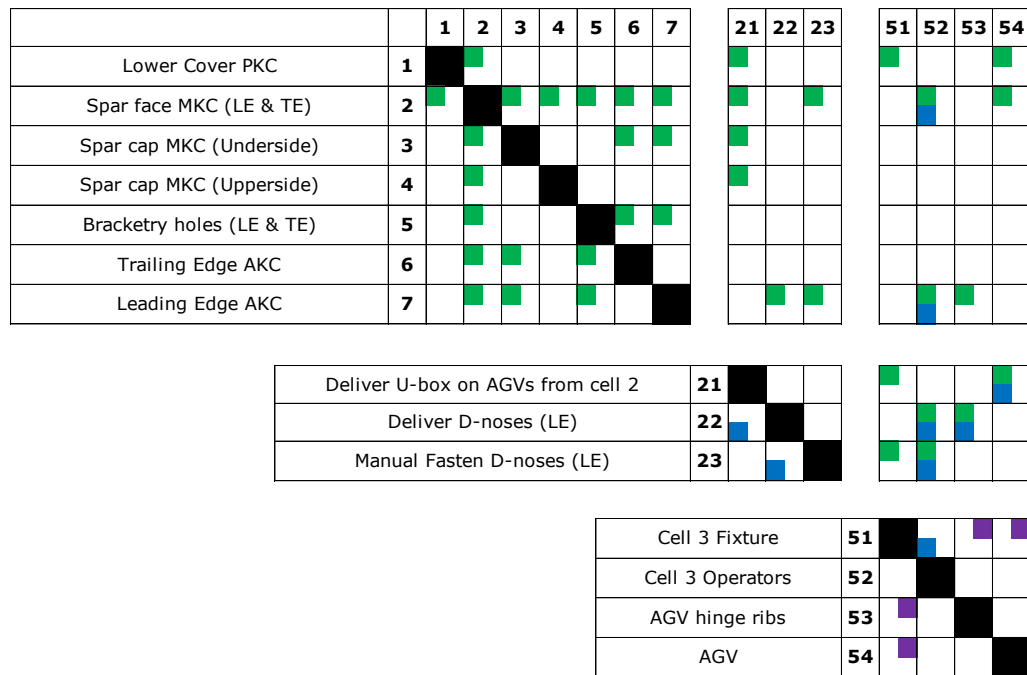


Figure 86. Cell 3 PPS DSM

Table 22. Cell 3 Processes

Process:		Equipment:
10 Deliver U-box on AGVs from Cell 2 20 Deliver D-noses 30 Manually fasten LE D-noses (part-to-part)		- AGVs for U-box - Fixture - AGVs for D-noses
Estimated capabilities:	Assembly should be hole-to-hole, however if hole-to-hole is not possible then these cells can be used to facilitate additional drilling processes to produce holes full size (part-to-part)	
Estimated Rates:	12 hour cycle time (1.5 shifts) - function of no. of operators and no. of holes - Automation is a possibility for high rate requirements	
Assumptions:		
- High precision machining in cell 1 will achieve part-to-part assembly - D-nose components can be manually handled - All components are accessible at nominal working height - Wingbox is rigid enough to support the additional weight of the added componentry - Manual workers have enough room to operate to meet rate even when at saturation		

6.6.1.7 Cell 4

Rib-setting is a complex process to 'best-fit' ribs to constrain wingbox geometry. AD specifies the cell to be independent of all other cells for efficient ramp-up. Rib-setting constrains the wingbox into rigid geometry. The tooling and assembly system for correct rib setting is critical to the function of the wing. The system DSM was used to inform the interface design and sequence for setting the ribs (Figure 87). The DSM highlighted interactions which would normally be dependent on the designer to highlight. The System DSM shows a high density of interactions for rib setting. This reduced the design complexity because the DSM allowed the design team to visualise the system and design appropriate interfaces and control sequences with knowledge of surrounding elements, avoiding clashes and design errors.

The rib setting process is presented in Table 23. Figure 88 shows the cell concept overview. The wingbox arrives via AGV with hinge ribs and D-noses fastened; the major operation in cell 4 is the claiming of the hinge line prior to assembling the ribs. Machining and drilling the wingbox in cell 1 implies that there is little or no corrective force required from the TE tooling to achieve the hinge line AKC (± 0.15 mm concentricity) and lower cover PKC (± 1.2 mm). Once the hinge line is claimed then the ribs are located and fastened, this assembled constraint produces a rigid structure.

[illegible]

Figure 87. Cell 4 PPS DSM

Table 23. Cell 4 Process Overview

Process:		Equipment:
10 Load wingbox into supporting fixture 20 Claim hinge line 30 Deliver ribs on AGV 40 Position and clamp ribs to rib feet and rib posts 50 Drill, seal and final fasten ribs		• Fixture • Robot • Position & clamp module • Drill & fasten module
Estimated capabilities:	+/-0.2mm (general positional tolerance achievable with current technologies. Concept is dependent on drill spindle access which will require some interaction from design)	
Estimated Rates:	Estimate 12 hrs (1.5 shifts) per wing, scalable with multiple machines	
Assumptions:		
• The natural deflections of the u-box allow the hinge line to be claimed without overstepping the lower cover PKC (in the order of < 3 thou – light hand pressure applied by operators) • The rib assembly will provide enough strength and rigidity to hold the hinge line and lower cover KCs • Accuracy from part-to-part assembly of hinge ribs is sufficient that the hinge line can be claimed without any major corrective force • Robot can position ribs to wingbox with sufficient accuracy • Hole positions for securing ribs to rib feet and rib posts are within the spindle size of the automated tooling • Enough clamping force can be applied between the rib and rib-foot to allow one shot drilling.		

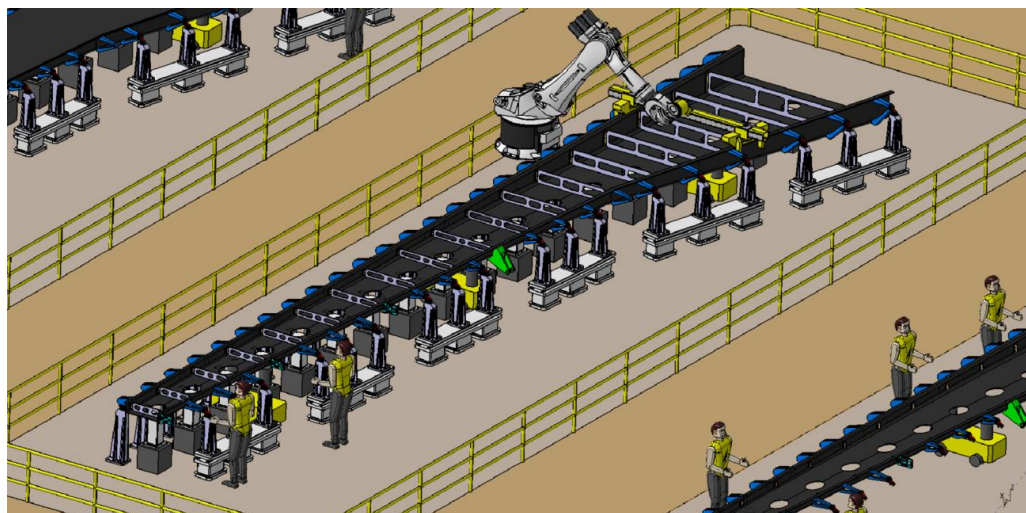


Figure 88: Cell 4 overview

Figure 89 presents a detailed view of the wingbox and fixture with annotated working principles to locate and constrain the wing geometry for rib setting. The TE is constrained to hold the hinge line geometry. The AD process specified tooling to be independent in specific areas, unlike a conventional fixture and can be quickly replaced for new geometries, thus satisfying characteristics for reconfigurability.

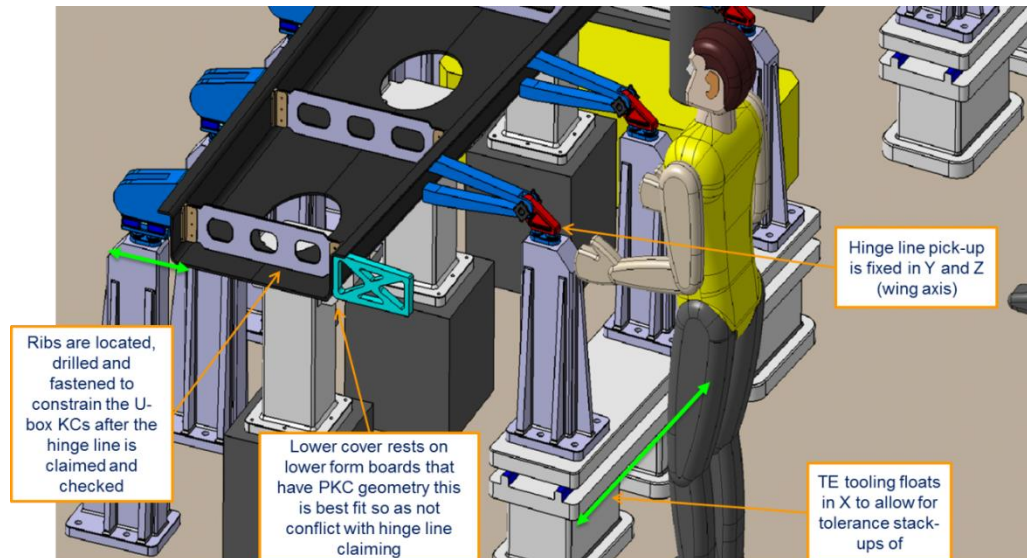


Figure 89: Close up of operations in cell 4

The ribs are positioned by 'best-fitting' to the spar caps (presented in Figure 91) so that the upper rib feet and spar cap profile match that of the inside surface of the upper cover. Process 40, Position and clamp ribs to rib feet and rib posts breakdown (Figure 90):

40.1 Ribs are collected by the end effector attached to dual robots.

40.2 Rib positioning aligns rib feet with spar cap to interface with upper cover. The design of the end effector achieves this with datum points that interface with the spar cap.

40.3 The ribs are clamped to the integrated rib feet and rib posts by one of the yokes.

40.4 A second yoke drills and fastens the ribs

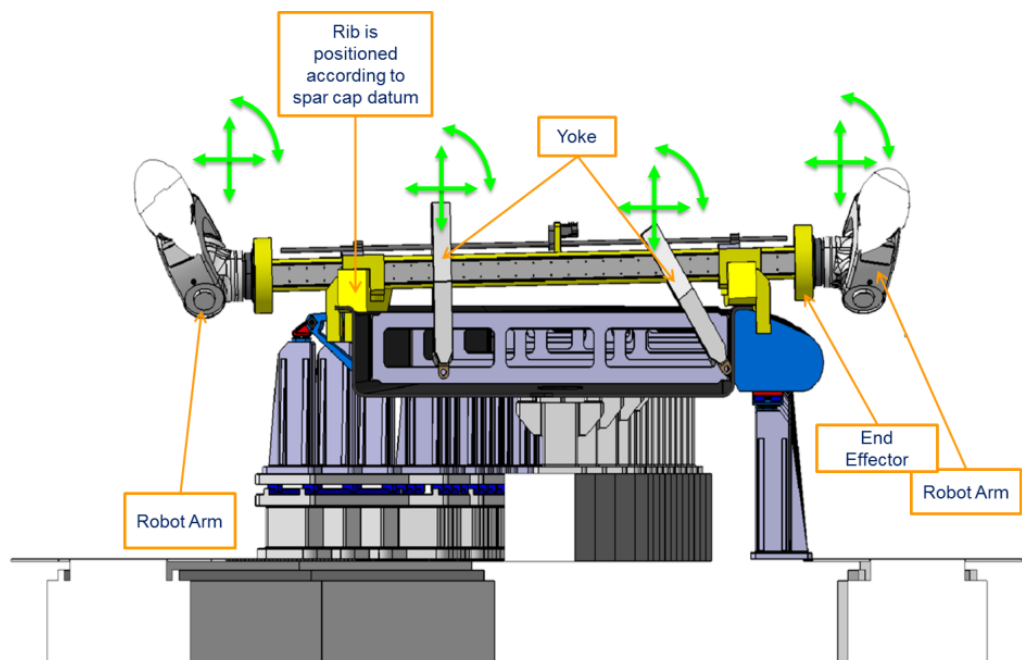


Figure 90. Working principle and DoF for rib setting

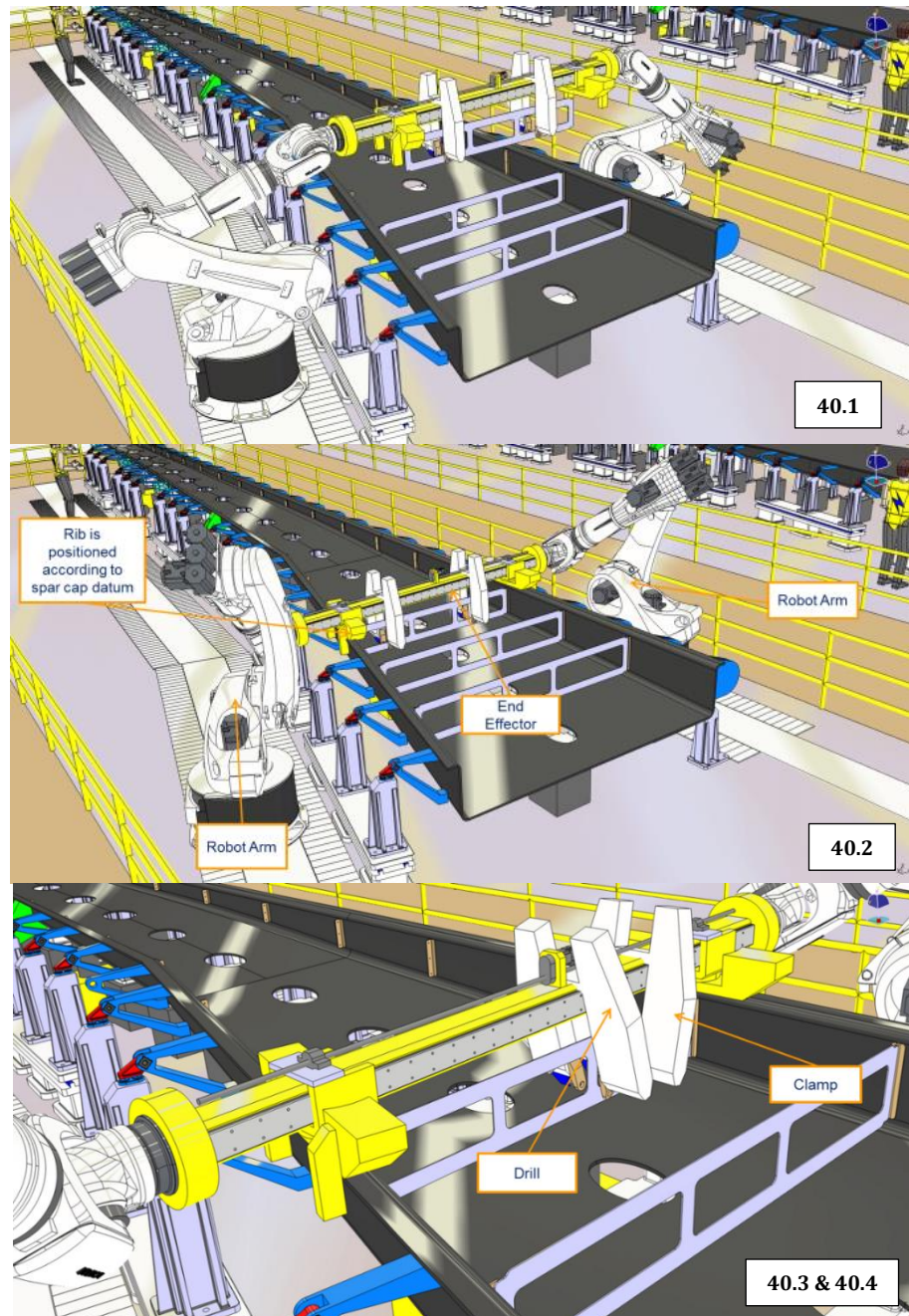


Figure 91. Cell 4 - Rib positioning and fastening machine, a breakdown of process 40.

6.6.1.8 Cell 5

The wingbox is now fully constrained with the addition of the ribs. The use of DSMs for 3D design is continued for cells 5 and 6. Product and Process MDM guides assembly sequences and logistics planning for location and final fastening of the cover. Spatial interactions in System DSM inform the dimensions of fixtures and AGVs to avoid clashes and ensure seamless loading and unloading. The upper cover drilling is carried out in cell 5, overview in Figure 93. Table 24 presents the assembly process for cell 5. The wingbox arrives from cell 4 via AGV, now a rigid wingbox assembly, and to reduce cycle time is orientated in flight orientation. The cover arrives via loading fixture and crane system from outside the main line. The wingbox is located in the fixture, the hinge line is located then the upper cover is located on the wingbox (similar to the A350 cup-and-cone method), drilled and slave fastened. The rib positioning method described in cell 4 potentially eliminates or significantly reduces metallic shimming operations implying the upper cover only requires sealing and cure prior to drilling.

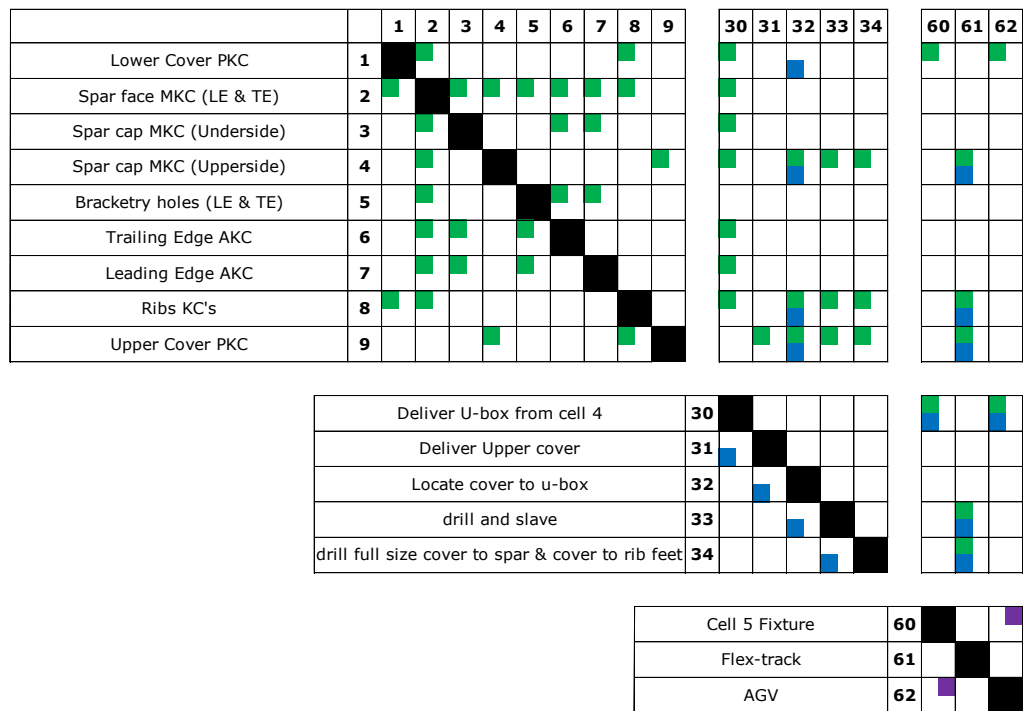


Figure 92. PPS DSM of cell 5

Table 24. Overview of processes in cell 5

Process:	Equipment:
10 Deliver wingbox from Cell 4 20 Deliver upper cover 30 Locate cover to wingbox 40 Drill & slave 50 Drill full size cover to spar & cover to rib feet	• Fixture • Flex-tracks • AGVs
Estimated capabilities:	≤ +/- 0.010" (Source: Electroimpact)
Estimated Rates:	• ≤ 4 holes-per-min • 12 hour cycle time (1.5 shifts) scalable with additional machines • Variable for rate increase/decrease
Assumptions: • Working height of operators is nominal • Flex-track machines can be automatically loaded if required • Datum holes and reference features will be possible in the wing skin • Machined spar cap will interface correctly with wing skin and close correctly	

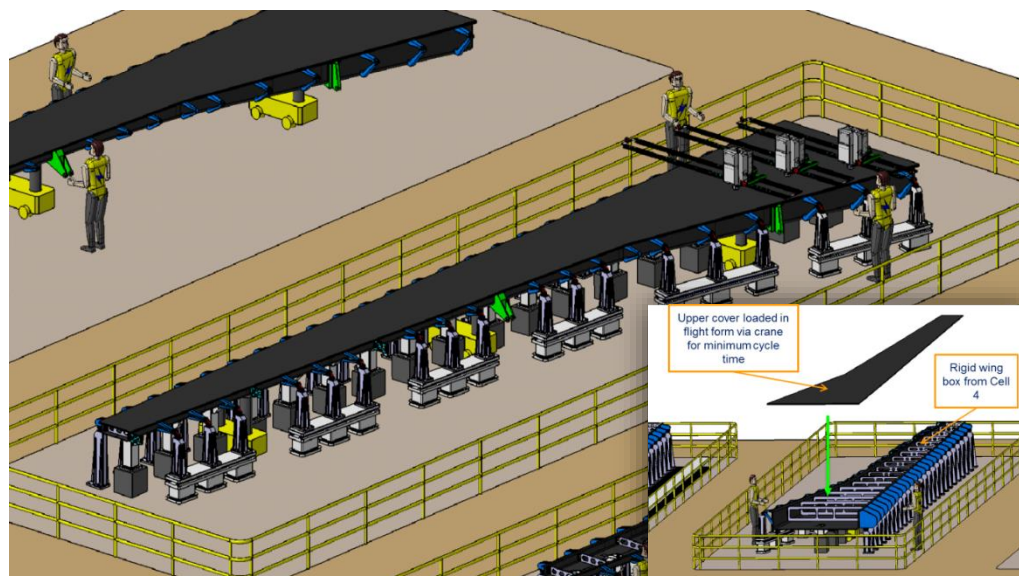


Figure 93. Overview of Cell 5. Inset bottom: Location of upper cover

6.6.1.9 Cell 6

The DSM is presented in Figure 94 for upper cover assembly. Upper cover removal for cleaning and reassembly for final fastening are carried out in Cell 6 (Figure 95). The wing arrives via AGV and the cover is removed using a fixture and overhead crane system (Table 25). This process is ramped up by adding labour to reduce cycle time.

	1	2	3	4	5	6	7	8	9	35	36	37	38	39	62	63	64	65	66
Lower Cover PKC	1																		
Spar face MKC (LE & TE)	2																		
Spar cap MKC (Underside)	3																		
Spar cap MKC (Upperside)	4																		
Bracketry holes (LE & TE)	5																		
Trailing Edge AKC	6																		
Leading Edge AKC	7																		
Ribs KC's	8																		
Upper Cover PKC	9																		
Deliver wing box from cell 5	35																		
De-slave and remove cover	36																		
Clean & seal	37																		
Relocate & Final fasten	38																		
Unload	39																		
Cell 6 Fixture	62																		
Lifting frame	63																		
Cleaning equipment	64																		
Cell 6 Operators	65																		
AGV	66																		

Figure 94. PPS DSM of cell 6

Table 25. Cell 6 Processes

Process:		Equipment:
10 Deliver wing box from Cell 5 20 De-slate and remove cover 30 Clean & seal 40 Relocate and final fasten		• Fixture • Lifting frame • Cleaning equipment
Estimated capabilities:	Skin transportation, alignment and assembly as per A350 (baseline)	
Estimated Rates:	Function of no. of operators, estimate 12 hrs (1.5 shifts)	
Assumptions: • A350 baseline is transferable technology • Manufacture of Wing skin is to CoS		

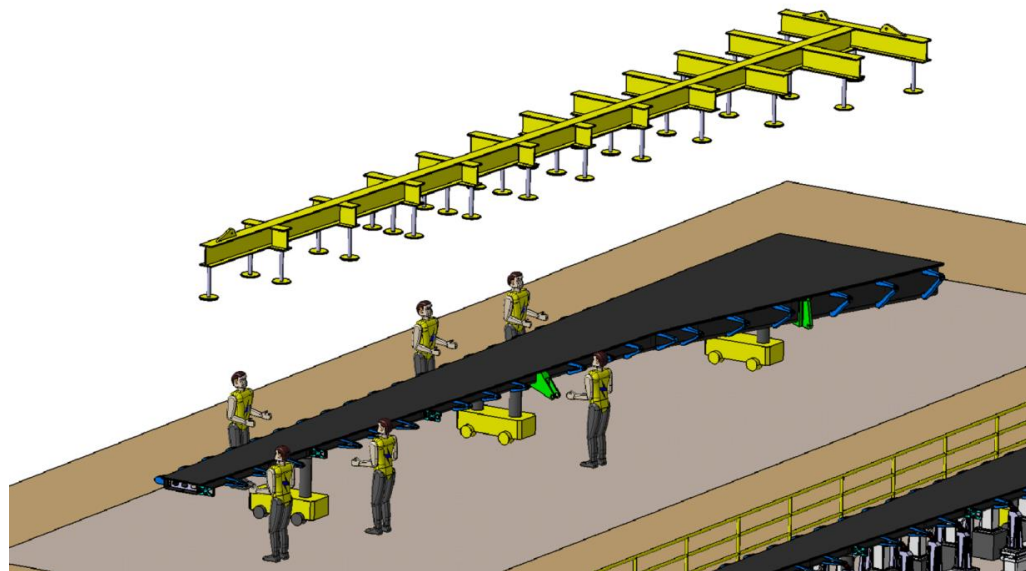


Figure 95. Cell 6 Overview - Upper Cover clean and final fasten

6.6.2 DSM to 3D CAD Summary

The 3D design is completed using DSMs to guide the design team in detail design. AD outlines the system architecture for scalability and customisation to embody the reconfigurability characteristics. The hierarchical approach of AD specifying customisable and scalable functions means high-level functions cascade into detailed designs consistent with higher level decisions and interactions. Cells are designed to be scalable by either adding automation or upgrade from manual to automated. Interactions specified in DSM construction inform the physical integration of the process and hardware into a working system. The interactions then inform the design team of the different ways in which elements of Product, Process or System interact. This in turn informs the detailed design of interfaces, assembly sequences and so forth. The designs are Airbus project deliverables for the build philosophy of NGCW. PPS DSM and 3D cell designs can now be used to model reconfiguration scenarios.

6.7 Reconfiguration Modelling: NGCW Production Rate Ramp-up Scenario

3D Cell designs are now complete and a PPS DSM represents the factory system. The DSM is used to map changes caused by reconfigurations which corresponds to the 3D CAD (Figure 96), thus highlighting the practical implications of reconfiguration. This section takes the reader through the methodology steps to reconfigure the design. The DSMs can be used to reconfigure a system design as well as test the system design is reconfigurable. The section shows how changes can be mapped and visualises the independence of the system. Any number of reconfigurations can be simulated as the DSM structure is updated for each implemented change. Equally, any number of changes can be tested using the DSM model.

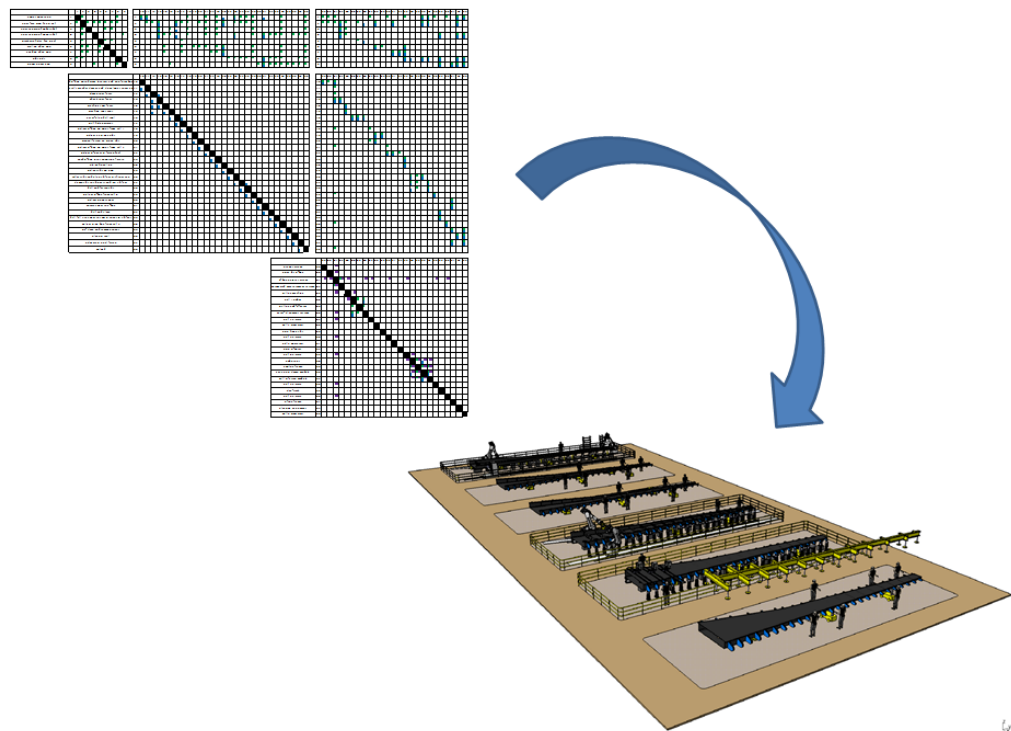


Figure 96. RAS DSM and corresponding 3D factory design for NGCW

A system designed from the outset to be scalable is able to increase production rate by adding modular elements to reduce cycle time, hence demonstrating a reconfiguration. Adding or changing elements introduces new interactions which have an associated time and cost to implement. The factory DSM is used to model reconfigurations by changing or adding elements and mapping the new interactions to understand the impact on the assembly i.e. is the reconfiguration cost-effective. DSMs can be used effectively in the design stage to map changes to test the design and influence design. Equally, DSMs can be used for the duration of the lifecycle to test other potential reconfigurations. Generally, a system designed for independence should be more receptive to change.

6.7.1 Ramp-up Scenario

The reconfiguration modelling is demonstrated using a ramp-up scenario for NGCW. The scenario is also part of Airbus project deliverables and satisfies TRL2 objectives for NGCW industrialisation. Airbus TRL2 criteria states demonstrations at this level of readiness should show preliminary assessment of feasibility and concept and show benefits and costs at rough-order-of-magnitude (ROM). The scenario demonstrates a change in structure for increased demand to validate the methodology for RAS design. Change in structure has technical and financial implications for Airbus and the results of the case study are part of the maturation and industrialisation process which is the responsibility of R&D. The scenario was agreed with Airbus stakeholders and is based on ongoing concerted efforts to address ramp-up challenges. Production rates are based on A320 order spikes which have seen increases of more than 200 orders. A320 has been ramped up several times by commissioning new fixtures which take 2 years to build. The ramp-up time has caused delays in deliveries and contributed significantly to the current backlog. Historical data will be used to compare the NGCW RAS with A320 production.

6.7.2 Identify New Requirement

The first step of reconfiguration modelling is to identify the new requirements for demand increase or model change. Scenarios for other types of reconfiguration can also be tested such as new technology using the same principles. The requirement in this case is an order for 240 aircraft. Basic production calculations are used to calculate the required cycle time for the new rate increase.

$$\begin{aligned}
 &720 \text{ Aircraft per year} - \text{Ramp up} - 960 \text{ Aircraft per year} \\
 &\text{New Production rate (months)} = \frac{960 \text{ Aircraft per year}}{12 \text{ Months}} \quad (6.10) \\
 &\text{New production rate (months)} = 80 \text{ Aircraft Per Month}
 \end{aligned}$$

New production capacity is new production rate plus extra capacity to account for the backlog accrued in the time between new orders and the new system production rate. This backlog accrued could be a percentage based on the order book or an estimate of the reconfiguration time. A backlog of 120 is based on 6 months production of 20 aircraft per month that will accrue from current systems capacity limited to rate 60. The new rate requirement is rate 80 with capacity of 90 to clear backlog accrued during ramp up.

$$\begin{aligned}
 &\text{New production capacity (year)} \\
 &= \text{new production rate} + \text{spare capacity} \quad (6.11) \\
 &\text{New production cap. (months)} = \frac{\text{new production rate} + \text{spare capacity}}{12} \\
 &\frac{960 + 120}{12} = \text{rate 90}
 \end{aligned}$$

90 aircraft per month

$$\begin{aligned}
 &90 \text{ aircraft per 30 days at 24 hours (720 hours)} \\
 &\frac{720 \text{ hours}}{90 \text{ aircraft}} = 8 \text{ hours per aircraft} \quad (6.12)
 \end{aligned}$$

6.7.3 Determine elements added

Once the requirements for the new system are defined then the elements that are to be added are identified. For rate increase, scalable elements chosen in AD satisfy functions for rate increase. The rationale for determining elements to be added is based on engineering knowledge and how the designer chooses the implement a reconfiguration, for

NGCW this was carried out in a workshop with stakeholder input. Adding scalable elements increases *max* capacity and doesn't necessarily force a fixed output. Max possible rate is 90 aircraft but system can be reduced to rate 80 if needed by buffering delivery.

Table 26. Example of elements added to cell 1 for rate increase scenario

Cell	System element	Process element	Process time	Elements added	New process time
Cell 1	Crane system	Load wingbox onto datum locators and PKC form boards	0.5	-	0.5
	Fixture Spreader clamps	Install spreader clamps and claim lower cover PKC	0.5	-	0.5
		Clamp spar faces	0.5	-	0.5
	Automated measuring system	Check spar faces	0.5	-	0.5
	Milling machine	Machine spar faces	4.5	Milling Machine B	2.25
		Machine spar caps			
	Laser alignment system	Laser-align drill tool	4.5	Laser Alignment system B	2.25
	Robot end-effector	Drill hole patterns		Robot B End-effector B	
1 hour added for miscellaneous work			1		1
Cycle Time			12 hours		8 hours

6.7.4 Add elements to DSM and Map New Interactions

The elements chosen to increase rate are agreed by stakeholders and decision makers and then added to the system DSM. Cell 1 is used as an example to illustrate this shown in Figure 97. The new interactions are then mapped (Figure 98) and noted. This process is repeated for each cell for a complete factory. Interactions are mapped by the design team.

6.7.5 Create 3D CAD simulation

The reconfigured DSMs are used in similar fashion to update the 3D CAD and verify the reconfiguration is satisfactory with stakeholders. Figure 99 shows the new elements added to the existing 3D CAD. Figure 100 shows cell 1 reconfigured for rate 90. The DM specifies functions for scalability which are translated into independent modules of automation which are designed to increase rate when added. The independently scalable architecture allows cell 1 to quickly reconfigure from rate 60 to rate 90.

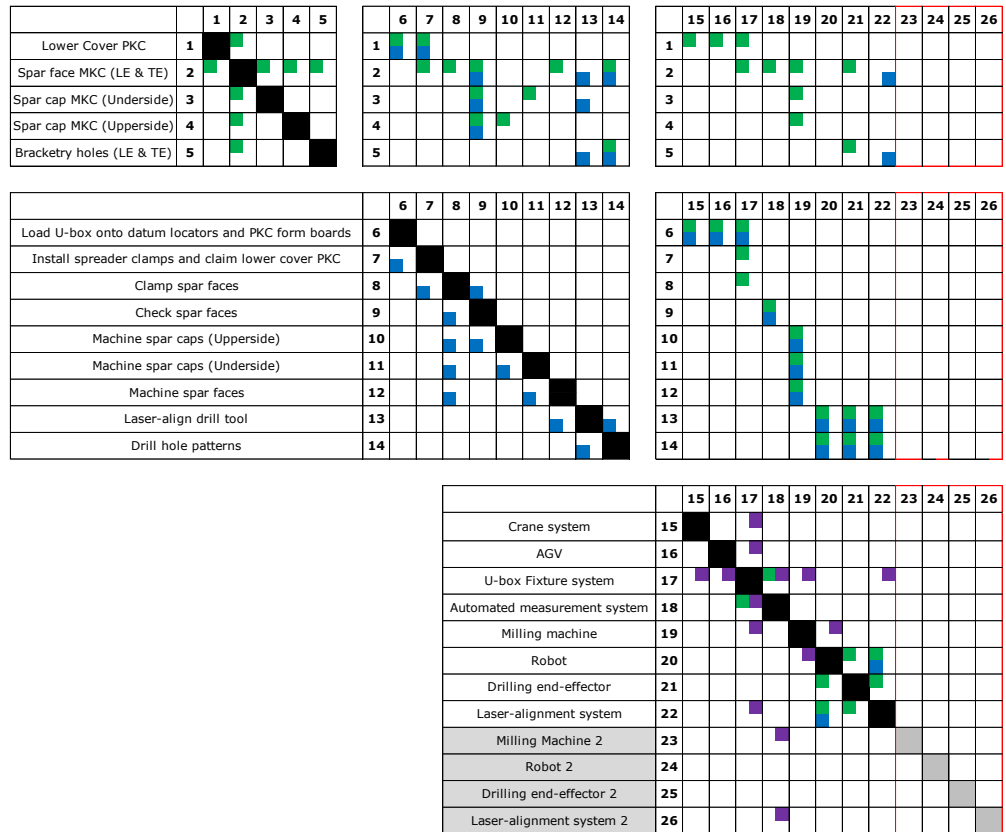


Figure 97. Cell 1 DSM with new elements added for reconfiguration

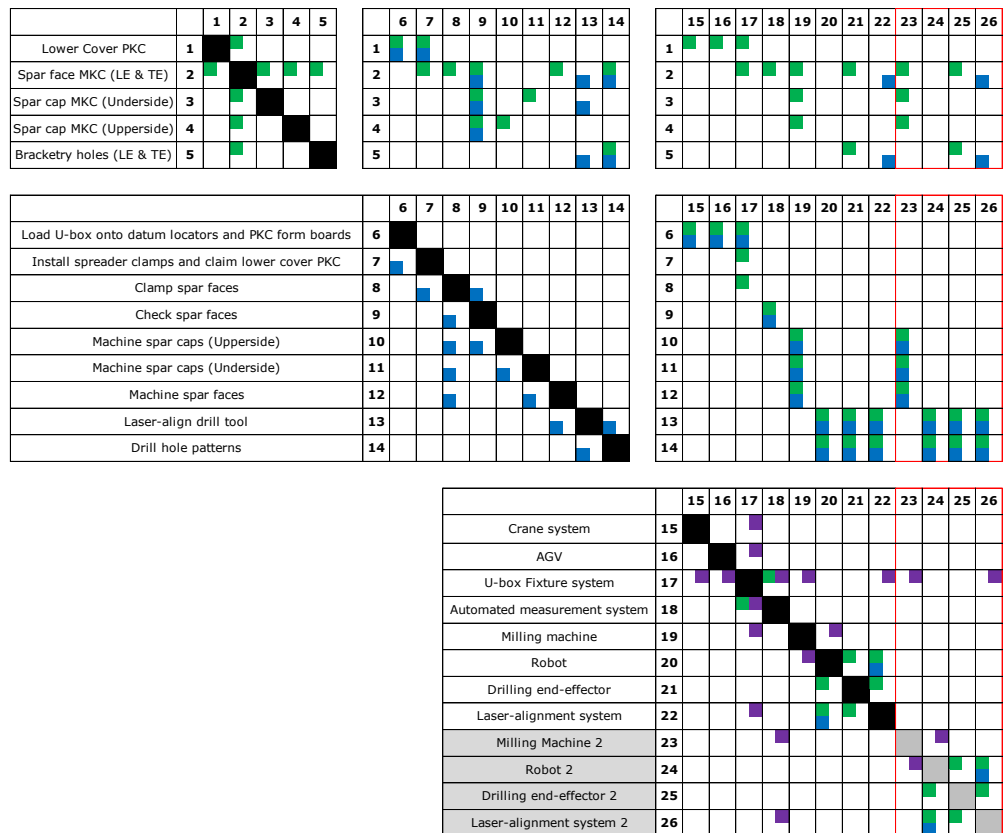


Figure 98. Cell 1 DSM model with added elements for reconfiguration

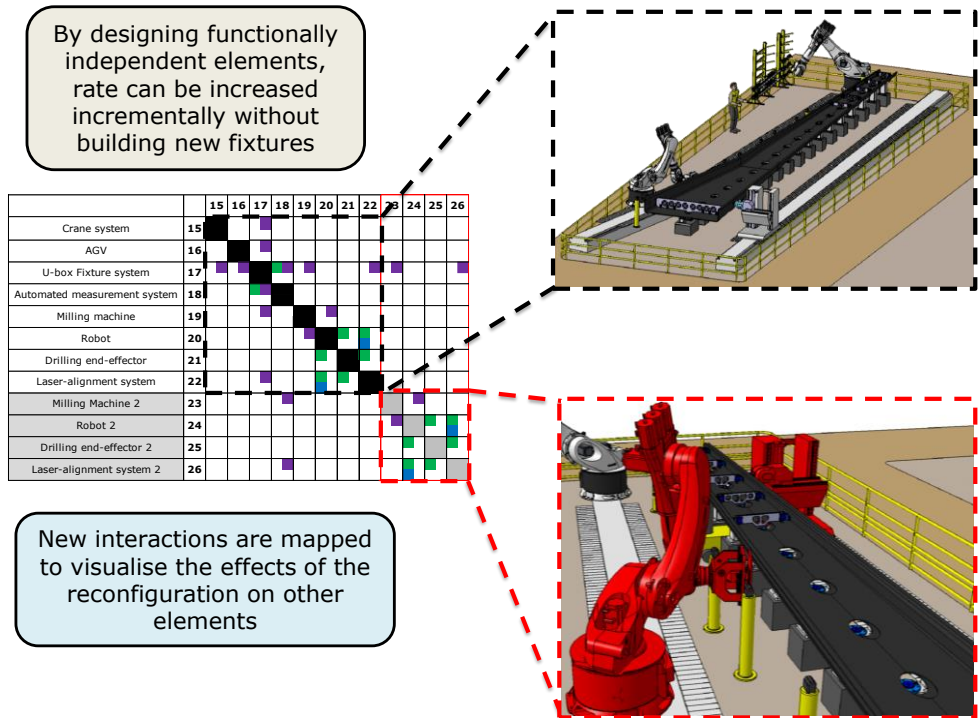


Figure 99. Scalable elements are added to the cell 1 system DSM to increase production rate. DSM elements correspond to automation equipment and tooling specified using the methodology

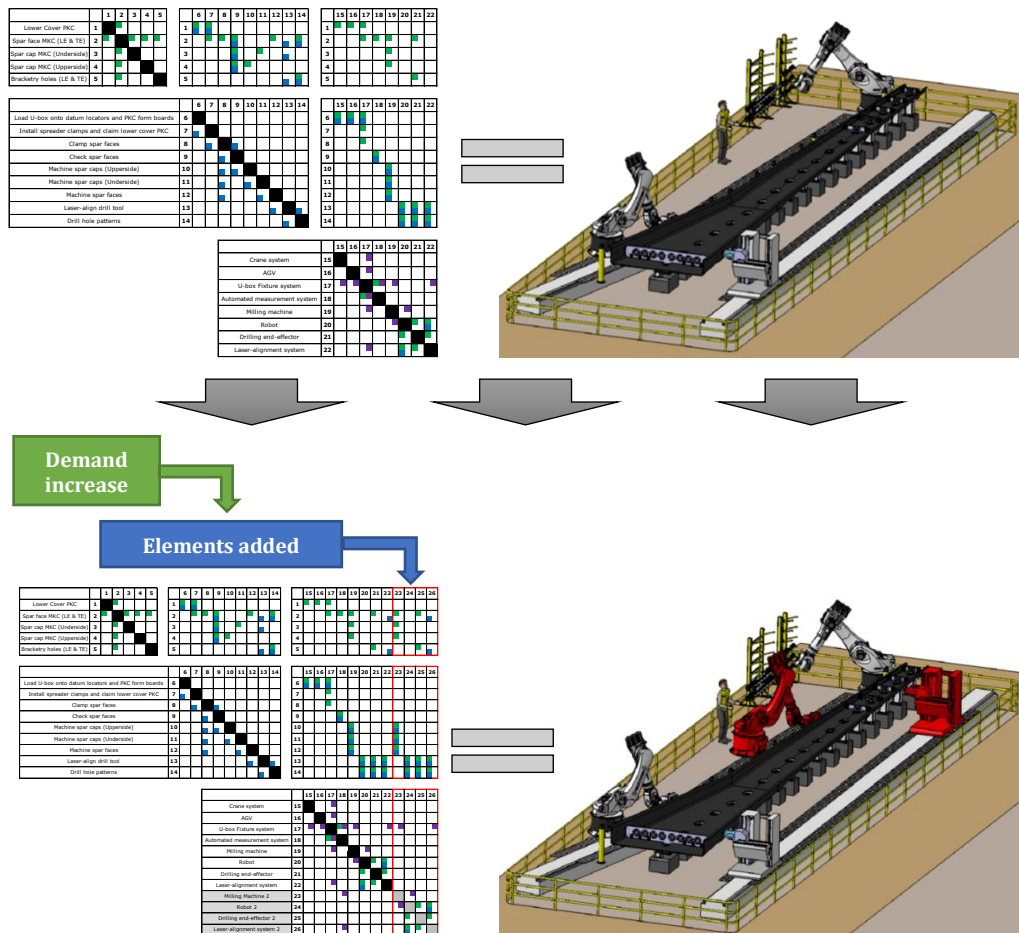


Figure 100. The scalable architecture allows cell 1 to quickly reconfigure from rate 60 to rate 90

6.7.6 RAS DSM Reconfigured

New interactions are mapped for the whole factory DSM and mapped to 3D CAD. Figure 101 presents the NGCW factory DSM reconfigured for rate 90 with new interactions. Figure 102 presents the two 3D CAD models for the original rate 60 assembly system and the RAS reconfigured for rate 90. The RAS DSM can be used to test multiple scenarios and reconfigured indefinitely to understand the implications for implementing reconfigurations.

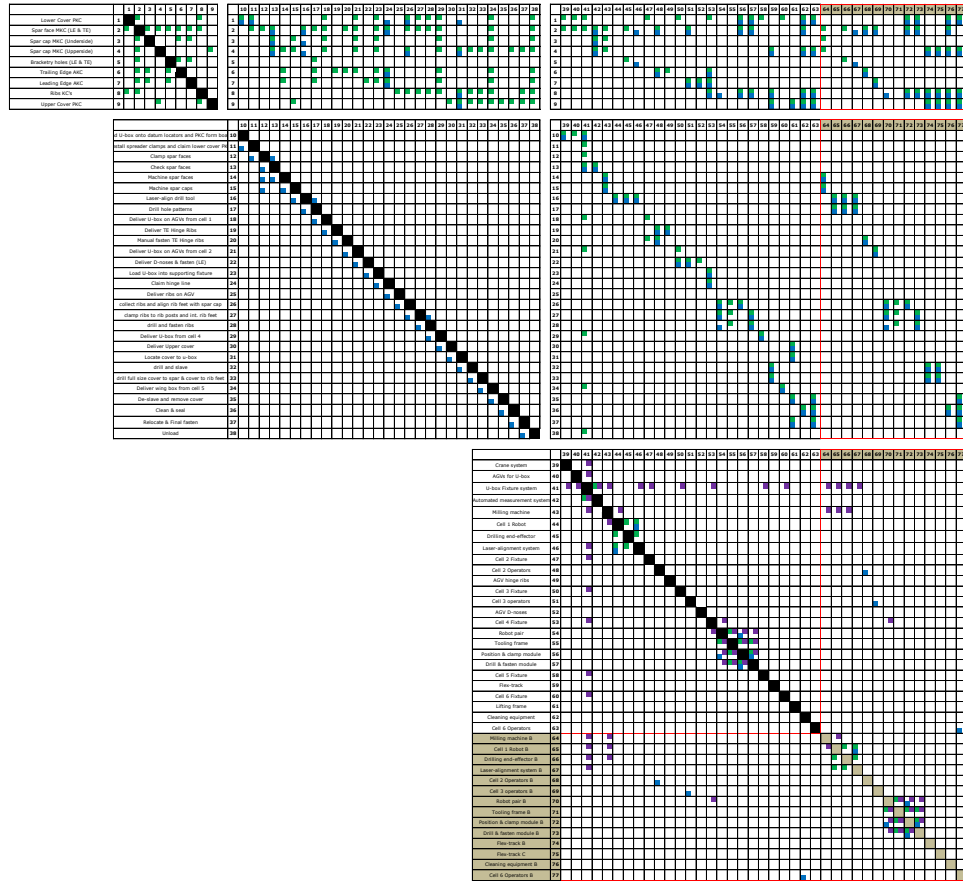


Figure 101. Factory DSM with elements added for reconfiguration

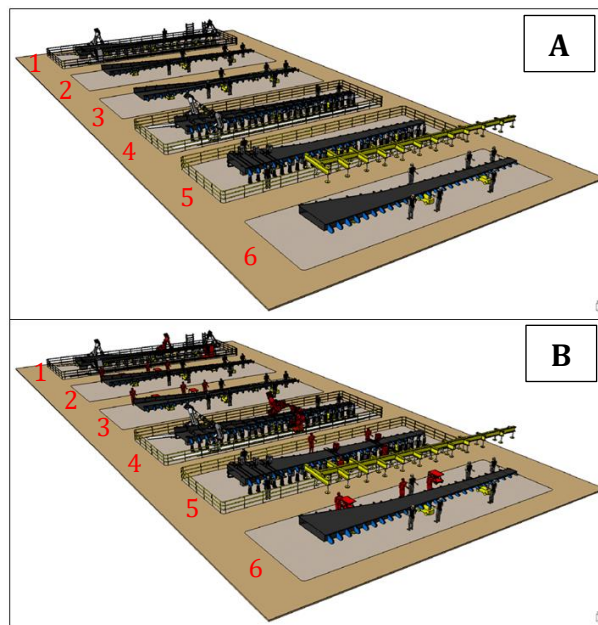


Figure 102. Factory layout for rate 60 (A) and reconfigured factory for rate 90 (B)

6.7.7 Identify Elements Affected

New interactions don't necessarily equal a part that needs to be modified, particularly if it is a proximity interaction. All elements with a new interactions are listed to be reduced to a list of elements to add or modify. Compiling a list in this way serves to guide the reconfiguration planning and is used for calculating specific costs. Some interactions only require an update in documentation whereas some require extensive engineering work. The following section addresses how the methodology is used to calculate time and cost to reconfigure based on the reconfigured DSM.

Table 27. System elements affected

Added element	Elements affected	Interaction	Description
Milling machine B	U-box fixture	Proximity	Machining path must not collide with fixture
	Cell 1 Robot	Proximity	Machining path must not collide with robot drilling
	Cell 1 Robot B	Proximity	Machining path must not collide with robot drilling
Cell 1 Robot B	Drilling end-effector B	Mechanical	End-effector is mounted to robot
	Laser Alignment System	Physical, Process	Laser alignment system feeds robot positioning
Drilling end-effector B	Laser Alignment System	Physical	Tracker target located on end-effector
Laser-alignment system B	-	-	-
Cell 2 Operators B	Cell 2 Operators	Process	Operators are integrated with current process
Cell 3 operators B	Cell 3 Operators	Process	Operators are integrated with current process
Robot pair B	Cell 4 Fixture	Proximity	Robot path must not collide with fixture
	Tooling frame	Mechanical, proximity	Tooling frame is mounted to both robots, robot paths must clear tooling frame
	Position & clamp module	Process, proximity	Positioning linked to robot control, robot path must not collide with module path
	Drill & fasten module	Proximity	Robot path must not collide with module path
Tooling frame B	Position & clamp module	Mechanical, proximity	Module slides on tooling frame rail, module must clear tooling structure
	Drill & fasten module	Mechanical, proximity	Module slides on tooling frame rail, module must clear tooling structure
Position & clamp module B	Drill & fasten module	Mechanical, proximity, process	Modules connect during assembly, control systems are shared
Drill & fasten module B	-	-	-
Flex-track B	-	-	-
Flex-track C	-	-	-
Cleaning equipment B	-	-	-
Cell 6 Operators B	Cell 6 Operators	Process	Operators are integrated with current process

Table 28. Process elements affected

Added Element	Process Affected	Interaction	Description
Milling machine B	Check Spar Faces	Physical, Process	Update machining program to use two machines
	Machine Spar Faces	Physical, Process	Update machining program to use two machines
Cell 1 Robot B	Laser-align drill tool	Physical, Process	Update robot programming to use two robots
	Drill hole patterns	Physical, Process	Update drilling process documentation for two robots
Drilling end-effector B	Laser-align drill tool	Physical, Process	Integrate new laser alignment and new end-effector into process
	Drill hole patterns	Physical, Process	Update drilling process documentation for two drilling tools
Laser-alignment system B	Laser-align drill tool	Physical, Process	-
	Drill hole patterns	Physical, Process	-
Cell 2 Operators B	Manual fasten TE Hinge Ribs	Physical, Process	Integrate new operators
Cell 3 operators B	Manual fasten LE D-noses	Physical, Process	Integrate new operators
Robot pair B	Collect ribs and align rib feet with spar cap	Physical, Process	Integrate new automation set and update process documentation
	Clamp ribs to rib posts and int. rib feet	Physical, Process	-
	Drill and fasten ribs	Process	-
Tooling frame B	Collect ribs and align rib feet with spar cap	Physical	Process update for new tooling
	Clamp ribs to rib posts and int. rib feet	Physical	Process update for new tooling
	Drill and fasten ribs	Physical	Process update for new tooling
Position & clamp module B	Collect ribs and align rib feet with spar cap	Physical, Process	New automation to be integrated with existing process
Drill & fasten module B	Clamp ribs to rib posts and int. rib feet	Physical, Process	New automation to be integrated with existing process
	Drill and fasten ribs	Physical, Process	New automation to be integrated with existing process
Flex-track B	drill and slave	Physical, Process	New automation to be integrated with existing process
	drill full size cover to spar & cover to rib feet	Physical, Process	New automation to be integrated with existing process
Flex-track C	drill and slave	Physical, Process	-
	drill full size cover to spar & cover to rib feet	Physical, Process	-
Cleaning equipment B	Clean & seal	Physical, Process	Additional toolsets for new operators
Cell 6 Operators B	De-slave and remove cover	Physical, Process	Additional operators integrated into existing process
	Clean & seal	Physical, Process	Additional operators integrated into existing process
	Relocate & Final fasten	Physical, Process	Additional operators integrated into existing process

Table 29. Product Feature elements affected

Added Element	Product Feature Affected	Interaction	Description
Milling machine B	Spar face MKC (LE & TE)	Physical	Spars now machined using dual automated milling
	Spar cap MKC (Underside)	Physical	Spar caps now machined using dual automated milling
	Spar cap MKC (Upperside)	Physical	Spar caps now machined using dual automated milling
Cell 1 Robot B	-	-	-
Drilling end-effector B	Spar face MKC (LE & TE)	Physical	New end-effector used for drilling spars
	Bracketry holes (LE & TE)	Physical	New end-effector used for drilling spars
Laser-alignment system B	Spar face MKC (LE & TE)	Process	New alignment system measures spars
	Bracketry holes (LE & TE)	Process	New alignment system measures spars
Cell 2 Operators B	Spar face MKC (LE & TE)	Physical, Process	Additional operators assemble TE
	Trailing Edge AKC	Physical, Process	Additional operators assemble TE
Cell 3 operators B	Spar face MKC (LE & TE)	Physical, Process	Additional operators assemble LE
	Leading Edge AKC	Physical, Process	Additional operators assemble LE
Robot pair B	Ribs KC's	Process	New robots set rib position
Tooling frame B	-	-	-
Position & clamp module B	Lower Cover PKC	Physical, Process	Positions & clamps ribs to integrated rib feet
	Spar face MKC (LE & TE)	Physical, Process	Positions & clamps ribs to rib posts
	Ribs KC's	Physical, Process	Sets Rib KCs and clamps before drilling
Drill & fasten module B	Lower Cover PKC	Physical, Process	Drills ribs to integrated rib feet
	Spar face MKC (LE & TE)	Physical, Process	Drills ribs to rib posts
	Ribs KC's	Physical, Process	Fastens ribs to U-box to create wingbox
Flex-track B	Spar cap MKC (Upperside)	Physical, Process	Added flex-track drills upper cover to spar cap
	Ribs KC's	Physical, Process	Added flex-track drills upper cover to rib feet
	Upper Cover PKC	Physical, Process	-
Flex-track C	Spar cap MKC (Upperside)	Physical, Process	-
	Ribs KC's	Physical, Process	-
	Upper Cover PKC	Physical, Process	-
Cleaning equipment B	Wing-box assembly	Physical, Process	KC's unaffected
Cell 6 Operators B	Wing-box assembly	Physical, Process	KC's unaffected

6.7.8 Identify Elements Modified & Calculate Time and Cost

The time and cost to add and modify elements is then calculated from the list of elements affected. Elements unaffected are ignored. A breakdown of work for reconfiguration time is presented in

Table 30. Work packages are integrated based on interactions and grouped appropriately so that work can be done as independently as possible. As the cells are separate they can be reconfigured simultaneously. Therefore, the reconfiguration time is considered as the longest cell to reconfigure; which is cell 1. This step is used to firstly estimate investment costs in reconfigurations by using the added elements and assessing the effort needed to implement the reconfiguration. A decision can be made based on strategic outlook. Each Product, Process or System element has a corresponding cost. Grouped elements have a corresponding time estimation to be fully operational in the cell. Cost and time factors are based on the JAM demonstrator cost model, also developed for Airbus (Naing 2004). This process can be used to compare investment options for different reconfiguration scenarios. Also, implementation work can be planned and structured with suppliers and the design team. Estimations of total costs of the reconfiguration are presented in Table 31. Cost are estimated according to conventional methods at Airbus which is based on experience and ROM costs obtained from suppliers.

$$T_c = T_d + T_l + T_i$$

$T_d = \text{Design Time}$
 $T_l = \text{Lead Time}$
 $T_i = \text{Integration Time}$
 $T_c = \text{Total Time To Reconfigure Cell}$

(6.13)

Table 30. Total time for adding and modifying equipment and processes

	PPS element	Product Process or System	add/ change	Des- ign time	lead time	Integr- ation time	total time	cell time (days)	cell time (mths)
Cell 1	Milling machine B	S	A	0	90	60	150	190	6.33
	Cell 1 robot B								
	Drilling end-effector B								
	laser alignment system B								
	Check Spar Faces	Pr	C	10	0	10	20		
	Machine Spar Faces								
	Laser-align drill tool	Pr	C	10	0	10	20		
	Drill hole patterns								
Cell 2	Cell 2 operators B	S	A	0	30	5	35	40	1.33
	Manual fasten TE Hinge Ribs	Pr	C	0	0	5	5		
Cell 3	Cell 3 Operators B	S	A	0	30	5	35	40	1.33
	Manual fasten LE D-noses	Pr	C	0	0	5	5		
Cell 4	Robot pair B	S	A	0	90	30	120	160	5.33
	Tooling frame B	S	A						
	Position & clamp module B	S	A						
	Drill & fasten module B	S	A						
	Collect ribs and align rib feet with spar cap	Pr	C	20	0	20	40		

	Clamp ribs to rib posts and int. rib feet	Pr	C						
	Drill and fasten ribs	Pr	C						
Cell 5	Flex-track B	S	A	0	60	30	90	150	5.00
	Flex-track C	S	A						
	drill and slave	Pr	C	30	0	30	60		
	drill full size cover to spar & cover to rib feet	Pr	C						
Cell 6	Cleaning equipment B	S	A	0	10	10	20	45	1.50
	Cell 6 Operators B	S	A						
	De-slave and remove cover	Pr	C						
	Clean & seal	Pr	C						
	Relocate & Final fasten	Pr	C						
								Ramp-up max.	6.33

$$C_c = C_d + C_l + C_i \quad (6.14)$$

$C_d = \text{Design Cost}$
 $C_l = \text{Non-recurring Cost}$
 $C_i = \text{Integration Cost}$
 $C_c = \text{Total Cell Cost}$

Table 31. Total cost of adding and modifying equipment and processes

	PPS element	design cost (£)	Non-recurring cost (£)	integration cost (£)	total cost (£)	sum cost (£)
cell 1	Milling machine B	-	750,000	200,000	950,000	1,790,000
	Cell 1 robot B	-	500,000	200,000	700,000	
	Drilling end-effector B					
	laser alignment system B					
	Check Spar Faces	20,000	-	50,000	70,000	
	Machine Spar Faces	20,000	-	50,000	70,000	
	Laser-align drill tool					
	Drill hole patterns					
cell 2	Cell 2 operators B	-	250,000	20,000	270,000	620,000
	Manual fasten TE Hinge Ribs	20,000		20,000	40,000	
cell 3	Cell 3 Operators B	-	250,000	20,000	270,000	600,000
	Manual fasten LE D-noses	20,000		20,000	40,000	
cell 4	Robot pair B	-	750,000	200,000	620,000	2,070,000
	Tooling frame B					
	Position & clamp module B					
	Drill & fasten module B					
	Collect ribs and align rib feet with spar cap	200,000		50,000	250,000	
	Clamp ribs to rib posts and int. rib feet					
	Drill and fasten ribs					

cell 5	Flex-track B	-	800,000	100,000	900,000	2,200,000
	Flex-track C					
	drill and slave	100,000		100,000	200,000	
	drill full size cover to spar & cover to rib feet					
cell 6	Cleaning equipment B	20,000	100,000	100,000	220,000	420,000
	Cell 6 Operators B					
	De-slave and remove cover	100,000		100,000	200,000	
Total						£7,700,000

6.7.9 Reconfiguration Modelling Summary

A ramp-up scenario has been modelled for the case study to demonstrate the methodology and provide ROM data for Airbus project deliverables. Reconfiguration Modelling can be used to model a number of scenarios by adding elements and mapping the new interactions. These interactions form the basis for investment analysis of time and cost to reconfigure. The analysis is used by stakeholders for decision-making. The ROM data from Reconfiguration Modelling for ramp-up is used for investment analysis in the following section along with results of the project.

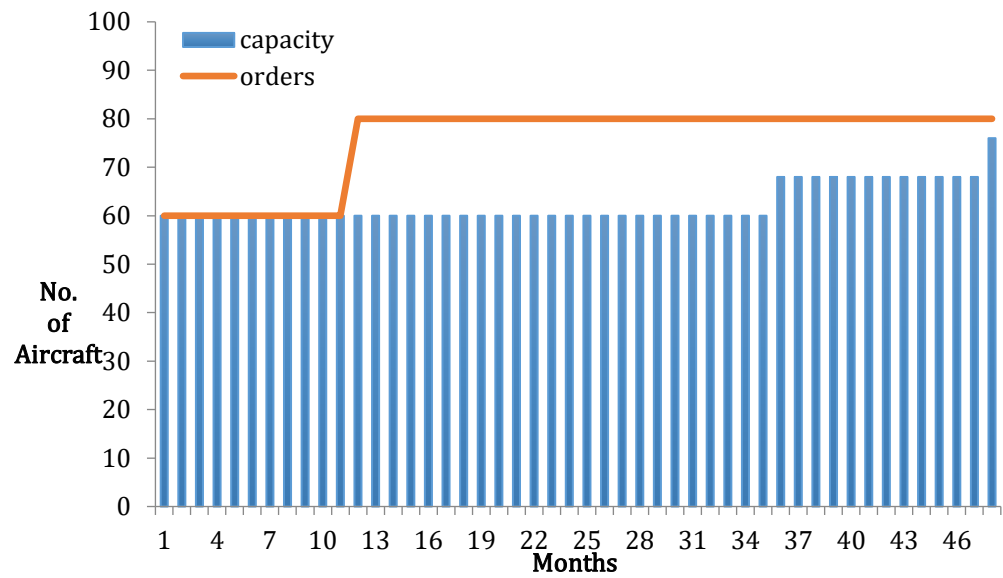
6.8 NGCW Case Study Results

Case study results are presented as evidence for the DM validation and Airbus project deliverables. A ROM comparison of ramp-up time, cost and production rate for a typical Airbus ramp-up scenario is presented. The data from NGCW case study is compared with current A320 production data to show possible benefits of using a RAS over the current assembly system. This is followed by summarised presentations of Airbus project deliverables and a TRL2 Assessment.

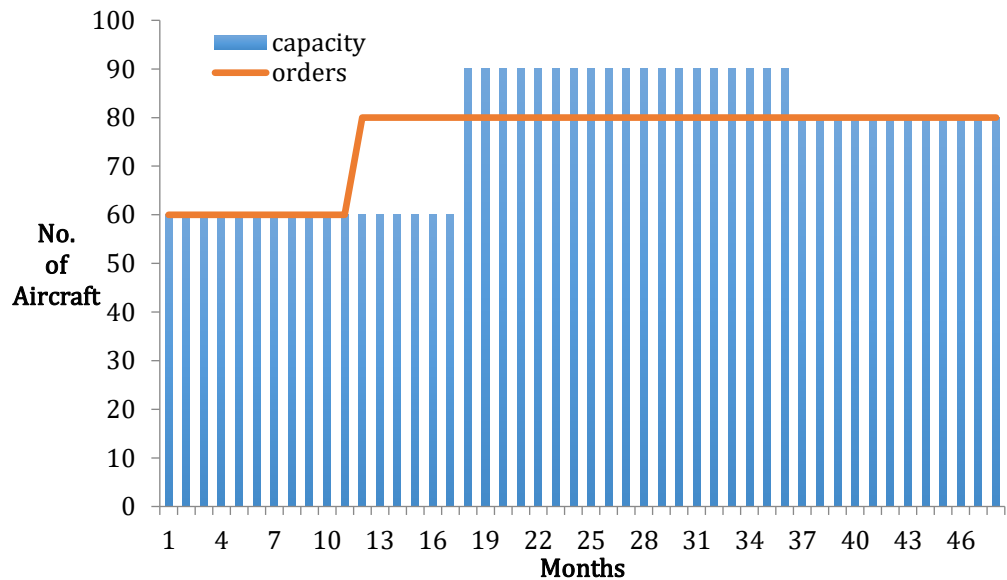
6.8.1 NGCW RAS Comparison with A320 Baseline

The NGCW RAS designed using the methodology in Chapter 6 is compared with current A320 production. The ramp-up scenario considers a typical order for single-aisle based on a recent A320 order. The two systems are compared for Ramp-up Rate, Production Capacity and Cost. NGCW ramp-up rate is taken from the reconfiguration modelling section and A320 ramp-up rate is taken from directly from Airbus. Graph 1 presents the ramp-up time using the current method of duplicating fixtures. For an increase of rate 60 to rate 80, ramp-up takes approximately 48 months. Graph 2 presents the ramp-up time for NGCW RAS designed with scalable architecture. For the same increase in rate, ramp-up takes approximately 6 months, as calculated in Section 6.7. This implies an improvement of 88%.

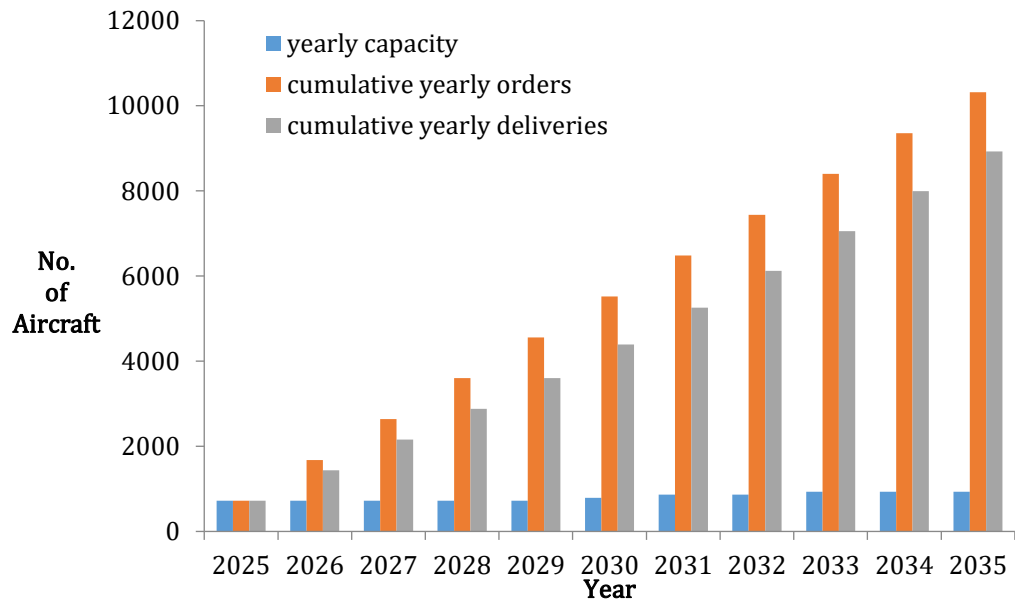
The effects of ramp-up time on production are presented in Graph 3 and Graph 4. A production run of 10 years is used for both systems to compare for backlog which is: total orders minus total deliveries. Graph 3 shows a projected backlog of 1392 aircraft in 2035 using the current ramp-up approach with an assembly system similar to A320. Graph 4 shows a backlog reduced to zero in 2028 using a RAS designed using the DM. A lower backlog increases revenues and ROI. Backlog is caused when production capacity cannot supply the new demand. Backlog grows when orders increase at a greater rate than production. Ramp-up increases the capacity to increase supply. New orders accumulate during the ramp-up period while the system is under-capacity. The new capacity must account for the orders accrued during the ramp-up period. Too long a ramp-up period can mean the new capacity is not sufficient to clear the orders accrued in the ramp-up period. Shortening the ramp-up period minimises the amount of orders that the new capacity must produce. Similarly, the extra capacity from the ramp-up must be large enough to account for the orders in the ramp-up period.



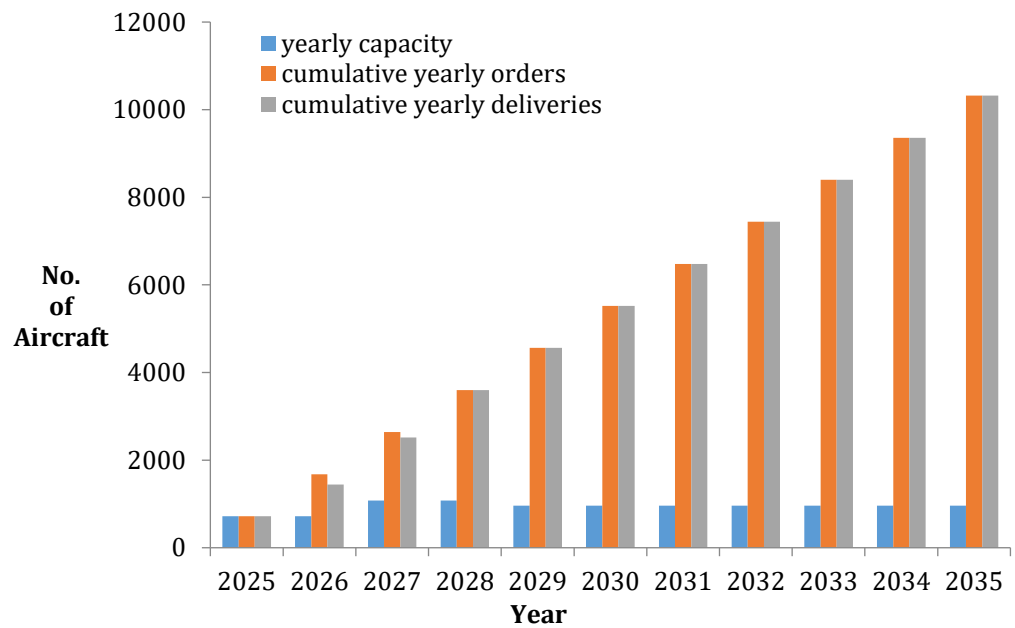
Graph 1. Current A320 assembly system ramp-up in response to increase orders from 60-per-month to 80-per month. Current ramp-up method takes 48 months to achieve 80-per-month capacity.



Graph 2. NGCW Reconfigurable Assembly System ramp-up in response to increase in orders from 60-per-month to 80-per-month. The system ramps up in 6 months to 90-per-month to account for orders accrued in the reconfiguration period before dropping capacity to 80-per-month.

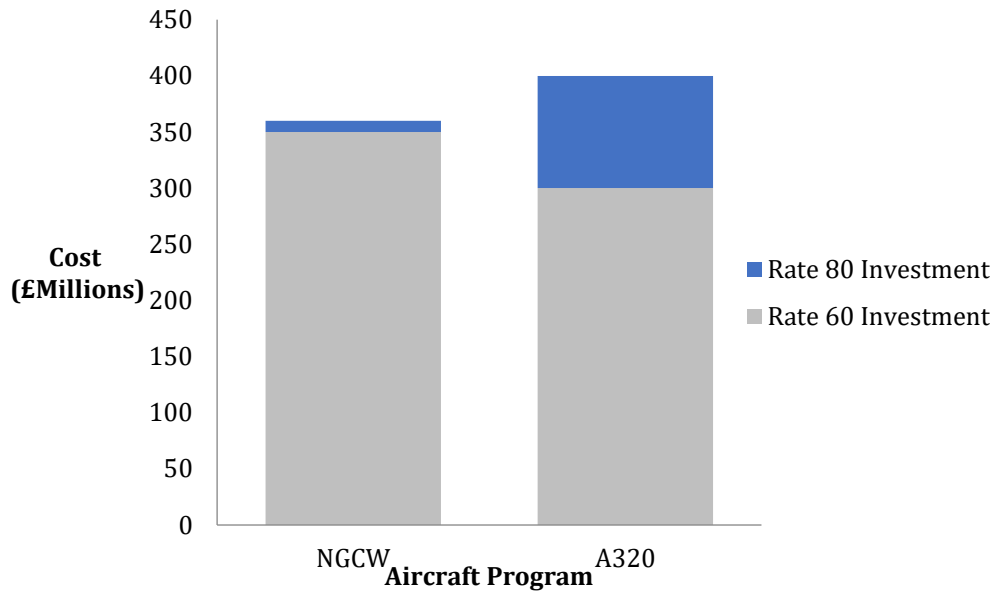


Graph 3. A projected 10-year production cycle of orders and deliveries using the current assembly system and ramp-up methods. The projected backlog accumulated is 1392 aircraft in 2035.



Graph 4. A projected 10-year production cycle of orders and deliveries using the NGCW RAS designed using the design methodology. The projected backlog accumulated is 120 aircraft in 2035

RAS method has 88% shorter ramp-up which means fewer orders are accrued. What's more, the capacity increase for NGCW RAS is 13% higher (90-per-month). This extra capacity is needed to supply the 6 months accumulated orders during the ramp-up period. The capability to quickly ramp-up capacity requires the RAS be designed with more technical functions to be able to quickly change in structure and functionality. Naturally this incurs an extra cost. Graph 5 compares ROM CapEx cost data for tooling which were provided by tooling suppliers and Airbus during the project. The initial investment for the RAS is 17% higher compared to the equivalent number of fixtures. This reflects the extra design complexity for functionality of the tooling to have scalable interfaces. However, the cost to ramp-up is 90% lower for RAS compared to commissioning the equivalent number of fixtures. And so represents a lower long-term investment. Overall investment in NGCW is 10% lower.



Graph 5. ROM costs for tooling CapEx for the ramp-up scenario case study comparing future and current ramp-up

6.8.1.1 Limitations and Assumptions

The case study results show apparent advantages to using the DM to create a RAS. However, these findings are subject to a number of limitations. Using one scenario to simulate ramp-up gives a limited view of how the system responds but is acceptable for Airbus requirements at this stage where the aim is to focus on technical feasibility of RAS. The data for ramp-up is taken directly from orders seen on the A320 assembly line. Scenarios will become more rigorous and detailed as design progresses. Any number of scenarios can be tested using the DSMs for modelling reconfigured systems. The ramp-up times were estimated by Airbus and tooling suppliers during the project. This is a common practice in aircraft development and times were agreed in stakeholder reviews and believed to be accurate. Similarly, ROM costs are based on quotations from tooling suppliers in the project and Airbus estimates. The costs are for tooling CapEx only which is the accepted norm for Airbus Manufacturing R&D at low TRL where non-tooling is usually out of scope. Future investigations should provide deeper fiscal analysis before investment. Labour was assumed to be equal between the two systems given the similar sizes and the likelihood that NGCW will have less labour because of higher automation and more integrated structures i.e. (less fasteners). Ramp-up times of the conventional assembly where based on current A320 production data and so is deemed valid. Costs of fixtures for conventional assembly where also provided by Airbus. Despite the limitations, results are satisfactory for Airbus at this stage in aircraft development. The Airbus TRL2 criteria stipulates 'ROM benefits' and ROM costs aren't necessary until TRL4 and detailed costs TRL6 respectively. As such, the findings presented are of the appropriate level of detail to inform Airbus stakeholders and support decision-making for future work.

6.9 Airbus TRL2 Assessment

The RAS design created using the DM was written up into a build philosophy and accompanying technical reports. Storyboards and tooling simulations were produced as part of project deliverables. The designs were reviewed periodically over a course of 2 years and the final designs were presented in a PDR to Airbus stakeholders. A PDR allows stakeholders to scrutinise all aspects of work and call for more clarity or evidence. Each cell design was critiqued by stakeholders for all aspects of feasibility and validity. The Airbus TRL methodology stipulates that the criteria for assessment should be outlined at the beginning of the project to allow for the extra scope needed to mature systems consisting of multiple technologies and subsystems. The Airbus TRL2 criteria for assessment was agreed with stakeholders where some criteria was omitted on grounds of scope and relevance. Figure 103 presents the Airbus TRL2 Assessment sign-off for NGCW

Industrialisation. The RAS design produced using the DM was reviewed at the end of the project and given Pass and Proceed recommendations.

TRL2 Criteria	Sufficient Work Conducted	Viability Established	
Performance Readiness	YES	TRL3-6	
Identification of potential applications and asstd reqts on A/C or into Prod. / Manuf. Process	n/a		
Set up criteria to select or reject applications			
Screening of new Generic Material or Technology to demonstrate properties of Technology			
Prel. asst of new Generic Material or Technology perf. vs specs and current solution			
Identification of inter-dependencies with other products			
Identification of potential scale-up issues and generation of mitigation plan	Report		
Engineering Readiness	YES	TRL3-6	
Identification and awareness of suitable sponsor or target End-User secured	n/a		
Identification of concepts for new Engineering capabilities if required and awareness of related relevant stakeholders			
Prel. asst of impact on AIRBUS Engineering (incl. skills, training...) and Supply chain (incl. Extd enterprise reqts)			
Assess potential for Certification issues, contravention of Regulation (A1091, REACH)	Report		
Manufacturing Readiness	YES		
Prel. asst of processes (prod., manuf,...) characteristics (small feasibility coupons), incl. Techno difficulties description	Report/PDR		
Prel. asst of Manufacturing concept	Report/PDR/CAD		
Prel. asst of impact on AIRBUS Manufacturing and Supply chain (incl. mono/multi source, ramp-up capability...)	Report/PDR/CAD		
Operations Readiness	YES		
Identification of repair process key characteristics and associated capabilities	n/a		
Prel. asst of impact on Maintainability, Availability, Reliability and Damage detection			
Value and Risk	YES		
ROM Estimate of benefits vs current solution and prel. asst of technical/industrial risks, incl. potential fallback solutions	Report/PDR		
Identification of related patents and patent holders			
Assess potential for AIRBUS patents, Intellectual Property issues	n/a		
IP Policy proposed according to strategy importance of Generic Technology			
Identification / summary of potential showstoppers (technical) and mitigation assessment	Report/PDR		
Route to TRL3 (business case, activities and asstd framework, means of demonstration and availability, level of effort...), according to solutions / implementation options	Report		
Review PASSED / NOT PASSED	PASS		
Technology Recommendation PROCEED / STOP / ON-HOLD		PROCEED	

Figure 103. Airbus TRL2 Criteria Assessment completed for NGCW Industrialisation project with the development of a RAS design

6.10 Chapter Summary

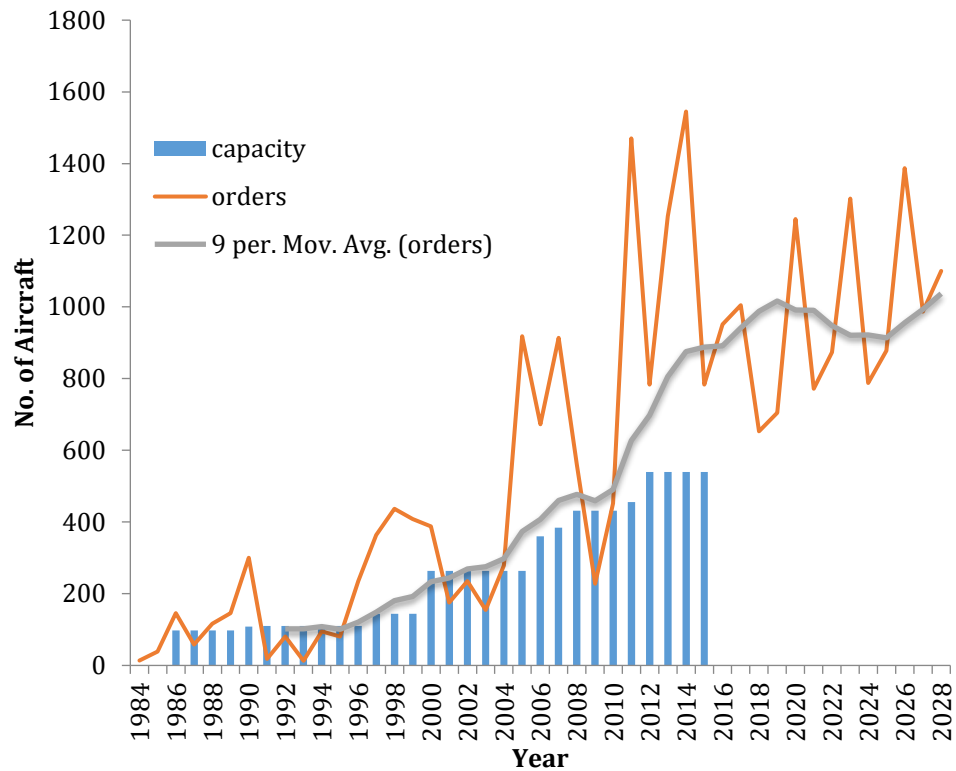
Chapter Six presents an industrial case study in conjunction with Airbus UK to validate the DM. The industrial project is assembly system design for an Airbus future aircraft – NGCW. The DM uses Airbus data to design a RAS for wing assembly. An Airbus ramp-up scenario was used to demonstrate scalability and compared with baseline production data. The findings indicate shortened ramp up and a comparable CapEx investment for tooling. The RAS should yield a lower backlog than the current approach. The RAS design passed an Airbus PDR review and TRL2 Assessment carried out by senior Airbus stakeholders. The next chapter presents a case study concerning the current aircraft and backlog.

Chapter 7 RAS Design Case Study: A320 High-Rate Production

This chapter details the second case study of the DM. The previous chapter focused on a future aircraft under development. The focus of this case study is to validate the methodology for current Airbus aircraft. The DM is used to design a RAS for a high-TRL product – the A320 wing currently assembled at the Broughton site. The methodology is applied to ASD at Airbus using Airbus data to validate the methodology for industrial use. Airbus forecast 22,000 single-aisle aircraft by 2033 including the A320 production backlog of 6193 (Airbus S.A.S 2014a). Airbus have commissioned a new pulse line for wing assembly to alleviate short-term backlog (Flight Global 2015a). Airbus current rate is 42 (Airbus S.A.S 2014c). Airbus expect the new production line to meet a monthly rate 60 in 2019 and 50 in 2017 (Airbus S.A.S 2015a). The case study is part of an ongoing project to reduce backlog and increase ramp-up capabilities. The case study investigates RAS as an alternative to pulse line assembly. The DM uses Airbus data to design the wing RAS. The design is then compared to a baseline based on a similar pulse line type assembly system. The following sections present the DM implementation and associated project details.

7.1 Customer Attributes Gathering

Customer Attributes were gathered from Airbus discussions and agreed in stakeholder review. Product Characteristics and Manufacturing System Characteristics captured for the RAS are based on current A320NEO wing design and the same assembly process to minimise certifications costs and expressly focused on high-rate production of A320NEO. In particular, ramp-up and scalability. Production data is based on forecasted orders. Between 2014 and 2033, Airbus forecast demand for 22,071 single-aisle aircraft including the current backlog (Airbus S.A.S 2014a). An Airbus aircraft is expected to replace current A320NEO sometime after 2025 (Airbus UK 2007; Goold 2010). A320NEO final deliveries are assumed to be 2028 to end production, this equates to an order book of approximately 19,000 A320 family variants. Over 14 years this is on average 1357 aircraft per year. Of course, orders are peaks and troughs so order spikes are chosen randomly to simulate market demand. These projected orders are presented in Graph 6. The RAS design will consider the current backlog. The data is taken directly from Airbus single-aisle orders and deliveries between 1984 to 2015 (Airbus S.A.S 2016a). Projected orders are presented for 2016 to 2028 and will form the production run used for the A320 RAS design. The volume of orders is based on Airbus market forecasts (*op. cit.*) and the order spikes are based on historical cases. A 9-year moving average of orders shows average increase of orders which bears more relevance to manufacturing because of the existing backlog having much greater magnitude than order increases. Table 32 presents a summarised list of Customer Attributes captured for the project. Main criteria for the system are increased ramp-up capability for high-volume production for A320 lifecycle. Airbus UK requires any future system to have demonstrable benefit over the current system. The current pulse line is a short term solution with fixed capacity but does have short term rate enablers following a similar principle to A350 manual to automated production.



Graph 6. Projected orders and current orders to data and current capacity

Table 32. Captured Customer Attributes

No.	Attribute Captured	Source
1	A320 Family Part Geometry	Project Launch Workshop 1
2	Use Current Assembly Process where possible	Project Launch Workshop 1
3	Consider current backlog	Project Launch Workshop 1
4	Consider pulse line lessons learnt so far	Project Launch Workshop 1
5	Use Airbus global forecast for orders source	Project Launch Workshop 1
6	Base ramp-up characteristics on historical order spikes	Project Launch Workshop 2
7	Use current supply chain network	Project Launch Workshop 2
8	Base prod. Run on earliest expected service entry of new aircraft	Project Launch Workshop 1
9	Delivery margin of 2 years after new aircraft service entry	Project Launch Workshop 2
10	Greater total maximum capacity than pulse line	Pulse Line Lessons Learnt
11	Scalable for rate increase	Pulse Line Lessons Learnt
12	Changeable for new technologies	Pulse Line Lessons Learnt
13	Assume 19,000 aircraft required between 2016-2028 (inc. backlog)	Project Launch Workshop 2
14	Observe current H&S	Project Launch Workshop 1
15	Minimise downtime	Project Launch Workshop 1
16	Observe current working conditions	Project Launch Workshop 1
17	Increase automation and flexibility of tooling	Project Launch Workshop 1
18	Comparable CapEx –benefit justifiable	Project Launch Workshop 1
19	Airbus ramp-up baseline is adding pulse lines	Project Launch Workshop 1
20	Production data comparisons both include current fixtures	Project Launch Workshop 2
21	Consider possibility of reconfigurations using high-TRL technology	Project Launch Workshop 2
22	Introduce provisions for automation in design stage (for retrofit)	Project Launch Workshop 2

7.2 Formalise Customer Needs

Customer Attributes were formalised into a set of Customer Needs suitable for design decomposition. Formalisation was a process of technical discourse by the design team employing conventional manufacturing engineering calculations. Customer Needs were approved by Airbus in a stakeholder review and are presented in Table 33. RAS and pulse line methods will both include the current production rate using the existing fixtures in production comparisons. The RAS must assemble all wing variants for A320 and have max production rate of 1680 per year. This will be ramped up in increments of 20 aircraft per month minimum in order to have significant effect on production. Given two 8hr shifts in line with current practice this equates to a cycle time of 10.4 hours for the RAS up to a maximum of 4.2 hours to meet rate 100. The system must utilise offline commissioning to maintain production during ramp-up and a third shift is available for integrating reconfigurations.

Table 33. A320 RAS Customer Needs

No.	Customer Needs
CN ₁	Assemble All A320 Variants Wing Primary Structures
CN ₂	Scalable in increments of rate 20 minimum
CN ₃	Production - Two 8hr shifts; 313 days per year
CN ₄	Max production rate 1680 per year
CN ₅	Max - min cycle time; 10.4 - 4.2 hours
CN ₆	Max capacity: RAS + current fixtures
CN ₇	Offline commissioning
CN ₈	Use existing assembly process SOIs
CN ₉	Comply with current H&S standards
CN ₁₀	Avoid recertification

7.3 Design Decomposition

Design decomposition proceeds in the same manner described in Chapters 5 and 6. Supporting rationale is given where appropriate to this particular case study for brevity. System Design Constraints are presented in Table 34. Constraints are precisely specified in this case study because of the mature product data and requirements. Constraints are decomposed into FR₁ and DP₁ and presented in Figure 104. Decomposition includes rate requirement in the hierarchy notation for convenience and to ensure FRs are properly translated into the right levels of capacity.

Table 34. A320 RAS System Design Constraints

No.	Constraints
C ₁	Primary Structure PKCs – Stage 01 All A320 variants
C ₂	Cycle Times (hrs): 10.4; 7.0; 5.2; 4.2
C ₃	Primary Structure Assembly SOIs – Stage 01
C ₄	Manning 24 hrs - Two 8hr production shift + one 8hr maintenance and integration
C ₅	Comply with current H&S standards
C ₆	Vertical Build
C ₇	Maximum ramp-up time per assembly cell: 12 months

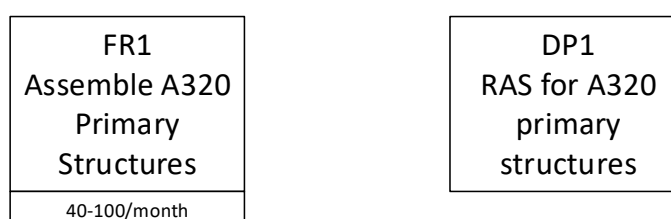


Figure 104. FR1 and DP1 for A320 RAS

The Customer Needs, Constraints and FR₁ are satisfied by DP₁ which embodies a system which is reconfigurable for rate. Design then follows AD procedure and zigzags from DP₁ which is decomposed into sub-functions (Figure 105).

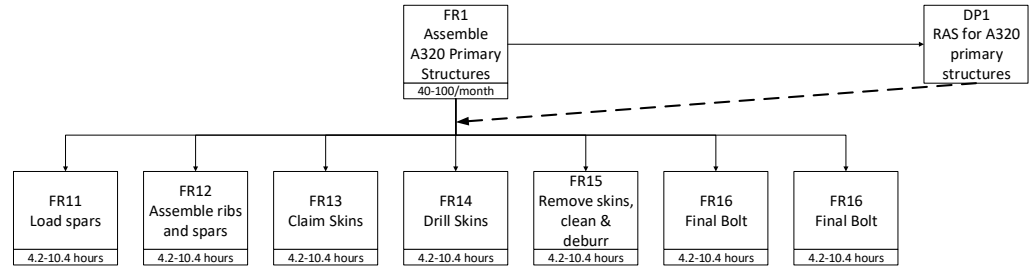


Figure 105. 'Zigzag' mapping process for FR₁-DP₁ to FR₁₁₋₁₆

Each sub-FR is consistent with FR₁ and DP₁ which act as constraints. From the sub-functions the designers choose suitable corresponding sub-DPs. Sub-DPs satisfy the corresponding sub-FRs and also must be consistent with DP₁. In doing this, requirements and indeed characteristics of a RAS can be specified at exactly the right level and thus embodied in the physical design. As RAS possess flexibility targeted to specific areas, some subsystems are a fixed architecture. Therefore, RAS are a mixture of scalable and non-scalable designs. Scalability can be achieved in a number of ways, such as adding robots or labour resource. Designers can choose how to satisfy the FRs based on their judgement. For instance, FR₁₁ – Load Spars is a relatively simple process to automate so a 4.2 hr cycle time is common. For slower cycle times, the system can remain idle when not in use at no detriment to cost. However, FR₁₂ – Assemble Ribs to Spars is a much more labour intensive process and so is best satisfied by a system which can systematically increase in rate. Designers may consider different options for certain DPs before finalising a solution. A complete set of second-level FRs and DPs is presented in Table 35. Second-level design matrix is also presented (Equation 7.1).

Table 35. Second level FRs and DPs for A320 RAS.

Second Level FR		Second Level DP	
FR11	Load Spars (10.4 to 4.2hrs)	DP11	Rail Handling System for Spars
FR12	Assemble Ribs to Spars (10.4 to 4.2hrs)	DP12	Reconfigurable Cell for Ribs and Spars
FR13	Claim Covers (10.4 to 4.2hrs)	DP13	Skin Positioning Cell
FR14	Drill Covers (10.4 to 4.2hrs)	DP14	Reconfigurable Drilling Cell
FR15	Remove Skins, Clean and Deburr (10.4 to 4.2hrs)	DP15	Cleaning Cell
FR16	Final Fasten Lower Cover (10.4 to 4.2hrs)	DP16	Scalable Final Fasten Cell (UC)
FR17	Final Fasten Upper Cover (10.4 to 4.2hrs)	DP17	Scalable Final Fasten Cell (LC)

Third-level FR-DPs are decomposed from second-level FR-DPs in the same manner described in Chapter 6. Each FR is written with specific cycle times to satisfy higher-level FRs to satisfy the requirements for rate and ramp-up. The designer specifies DPs suited to each FR. FRs can be satisfied by reconfigurable or non-reconfigurable solutions where needed based on the designers choice. Cycle times are specified according to the designers experience and judgement.

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \\ FR15 \\ FR16 \\ FR17 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \\ DP15 \\ DP16 \\ DP17 \end{Bmatrix} \quad (7.1)$$

FRs specified with larger cycle time ranges are then mapped to DPs that are scalable which enables ramp-up and capacity increase, such as FR₁₄₁. DP₁₄₁ is a scalable drilling module which can be added to shorten the cycle time. In contrast, FR₁₄₂ is satisfied by DP₁₄₂ which needn't be reconfigurable because the gantry solution is capable of achieving the shortest cycle time. The total cycle time for the third-level FRs is consistent with the parent FR which is mapped from Customer Needs. The designer proceeds in this way and specifies reconfigurable and non-reconfigurable solutions to provide exactly the capacity needed when needed. Table 36 presents the complete set of third-level FRs and DPs to make up a functional system structure made up of non-reconfigurable and reconfigurable solutions to provide necessary levels of reconfigurability to meet Customer Needs.

Table 36. Set of third-level FRs and DPs for A320 RAS.

Third-Level FR		Third-Level DP	
FR111	Load TE from delivery into handling frame (104 to 42mins)	DP111	TE Crane and Trolley
FR112	Load LE from delivery into handling frame (104 to 42mins)	DP112	LE Crane and Trolley
FR113	Constrain LE & TE (104 to 42mins)	DP113	LE & TE Frame with clamps
FR114	Translation in Y & Z into fixture (104 to 42mins)	DP114	Linear Rail and motor system
FR115	Constrain LE & TE KCs (104 to 42mins)	DP115	XYZ Customisable Fixture
FR116	Transfer to next operation (104 to 42mins)	DP116	Gantry System
FR121	Load Ribs to Spars (60 to 20mins)	DP121	Rib Cassettes and loading arm
FR122	Constrain Ribs to Spars (30 to 20mins)	DP122	Reconfigurable Manual Tacking
FR123	Drill Ribs to Spars (252 to 102mins)	DP123	Reconfigurable Manual Drilling
FR124	Fasten Ribs to Spars (252 to 90mins)	DP124	Reconfigurable Manual Fastening
FR125	Transfer to next operation (30 to 20mins)	DP125	Gantry Rail
FR131	Load Upper Cover (89 to 36mins)	DP131	Upper Cover Handling System
FR132	Constrain Upper Cover to Wingbox (89 to 36mins)	DP132	Upper Cover Fixturing
FR133	Temporary Fasten Upper Cover (89 to 36mins)	DP133	Reconfigurable Manual SSTF
FR134	Load Lower Cover (89 to 36mins)	DP134	Lower Cover Handling System
FR135	Constrain Lower Cover to Wingbox (89 to 36mins)	DP135	Lower Cover Fixturing
FR136	Temporary Fasten Lower Cover (89 to 36mins)	FR136	Reconfigurable Manual SSTF
FR137	Transfer to next Operation (89 to 36mins)	FR137	Gantry System
FR141	Drill Skins (562 to 232mins)	DP141	Scalable and Customisable Drilling Module
FR142	Transfer to Next Operation (62 to 20mins)	DP142	Gantry System
FR151	Remove Upper Cover (60 to 20mins)	DP151	Upper Cover Handling System
FR152	Remove Lower Cover (60 to 20mins)	DP152	Lower Cover Handling System
FR153	Clean and Deburr (384 to 172mins)	DP153	Cleaning Stations
FR154	Transfer Covers to Fastening Cell (60 to 20mins)	DP154	Transfer Rail
FR155	Transfer Wingbox to Next Operation (60 to 20mins)	DP155	Gantry System
FR161	Position Lower Cover (52 to 50mins)	DP161	Lower Cover Handling System
FR162	Fasten Lower Cover (520 to 182mins)	DP162	Reconfigurable Manual Fasten

FR163	Transfer to Next Operation (52 to 20mins)	DP163	Gantry System
FR171	Position Upper Cover (52 to 50mins)	DP171	Upper Cover Handling System
FR172	Fasten Upper Cover (520 to 182mins)	DP172	Reconfigurable Manual Fasten
FR173	Unload Wingbox (52 to 20mins)	DP173	Shipping Pallet and Crane

The supermatrix is constructed and presented in Figure 106. The design is a lower-triangular matrix and is therefore a decoupled design and satisfactory for physical integration using DSMs. The supermatrix is used in DSM modelling to ensure physical designs are consistent with the interactions mapped in the AD decomposition.

			DP1																															
			DP11					DP12				DP13							DP14	DP15				DP16		DP17								
			DP111	DP112	DP113	DP114	DP115	DP116	DP121	DP122	DP123	DP124	DP125	DP131	DP132	DP133	DP134	DP135	DP136	DP137	DP141	DP142	DP151	DP152	DP153	DP154	DP155	DP161	DP163	DP171	DP172	DP173		
FR1	FR11	FR111	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR112	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR113	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR114	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR115	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR116	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
	FR12	FR121	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR122	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR123	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR124	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR125	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
	FR13	FR131	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR132	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR133	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR135	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0			
		FR136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0			
		FR137	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0			
	FR14	FR141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0			
		FR142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0			
	FR15	FR151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0			
		FR152	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0			
		FR153	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0			
		FR154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0			
		FR155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0			
	FR16	FR161	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0		
		FR162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0		
		FR163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0		
	FR17	FR171	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0		
		FR172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0		
		FR173	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1		

Figure 106. Supermatrix constructed for A320 RAS

7.3.1 Design Decomposition Summary

Design decomposition for A320 is considered complete at the point which solutions and how to implement them are apparent to the designer. The hierarchy tree follows the same format as chapter 6 so is not shown. Extra decomposition or feasibility studies are carried out where necessary to provide extra clarity. The DM now progresses to DSM modelling stage using the system architecture and supermatrix.

7.4 DSM Modelling

DSM Modelling is carried out using the same rationale described in Chapter 6 so is not repeated. The DSMs are constructed and interactions are mapped to define a physical structure. The DSM construction process is carried out by the design team using the AD hierarchy and supermatrix. Sub-DPs are grouped into cells based on engineering rationale of the design team. Interactions are mapped for each DSM followed by mapping interactions between domains. DSMs Modelling is dependent on designer knowledge and frequent discussions among designers (Eppinger & Browning 2012). This case study used designer experience of A320 assembly and tooling design. Designers referred to process documentation throughout.

7.5 Map DSMs to 3D CAD

DSMs are presented for the complete assembly system. The complete factory DSM highlights interactions between cells. Mapping DSMs to 3D CAD translates customer needs into physical solutions by means of AD decomposition specifying the functions and corresponding system then by using decomposition to model a system made up of physical interactions consistent with design decomposition and supermatrix. The DSMs in this study are more detailed because of the more mature product data. The factory DSM is presented in Figure 107.



Figure 107. Complete Factory DSM for A320 RAS

The factory DSM shows a complete system view of the A320 RAS which is used for design. A complete systems view shows interactions between cells as well as interactions across domains which can go unnoticed in Airbus conventional design. Important cell-to-cell interactions highlighted using the factory DSM where noted by the design team and used

to develop working 3D designs. The system uses a moving fixture to hold the wing and transfer between cells via a gantry system. The DSM highlighted the proximity interaction between the fixture structure and cell structure which informed design to create 3D designs with sufficient clearance. The interactions between process and system domain also aided designers in developing a suitable process. These interactions typically go unnoticed until near production which usually involves extensive redesign which adds to costs and production delays. The factory DSM was also used to design the cover tooling and cover handling systems. The cover is 'handed over' to the fixture and so requires tooling to properly locate the covers. This handover process has many interactions between the covers, tooling and location processes. The highlighted interactions for mechanical, process and proximity interactions were used to design a system with suitable interfaces and avoid clashes and redesign. The system DSM is presented for each cell in the remainder of the section along with a description of the cell and working principles. Relevant aspects of the DSM mapping to 3D elements are discussed accordingly.

7.5.1 Cell 1 – Spar Loading

The PPS DSM is presented for Cell 1 in Figure 108. Cell DSMs are used for 3D design along with the Factory DSM to highlight inter-cell and inter-domain interactions. The impact of independence specified in the AD process can be seen with the modular sections of the system DSM.

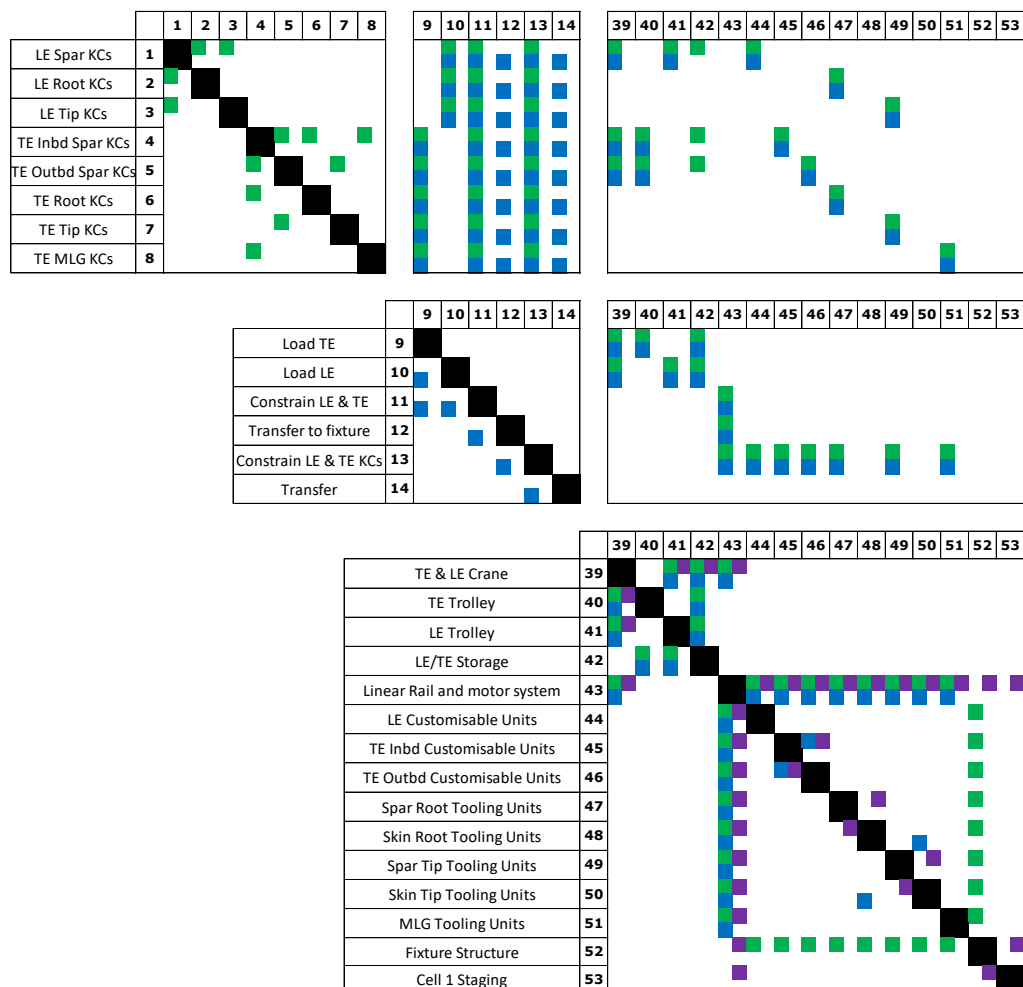


Figure 108. PPS DSM for Cell 1

TE and LE crane system comprises elements 39-42 and elements 43-53 comprise the spar loader system and fixture. The only interaction shared between these two modules is the mechanical, process and proximity interactions between the crane tooling and spar loader. This independent design supports reconfigurability where a set of elements can be modified without impacting on the other elements. Note, all tooling units (elements 44-

51) are all mechanically attached to the fixture structure which is highlighted by interactions. This allows the systematic design of a complex system. Note that most tooling units are independent from one another which is intended through AD. Modifying a part of the wing does now not require modification to all aspects of the fixture since tooling units can be modified independently. Thus enabling customisability. Figure 109 and Figure 110 show an overview of cell 1 with major assembly tooling systems. DSMs were used for designing interfaces ensuring 3D design is consistent with requirements set forth in AD hierarchy. Figure 111 presents the cell process of loading spars to MAF.

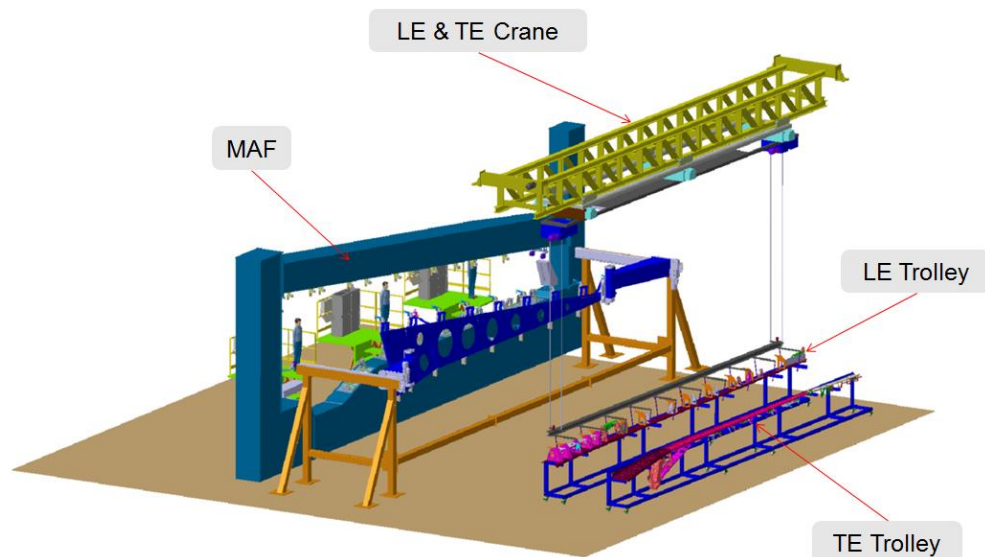


Figure 109. Overview of Cell 1 showing the MAF, LE & TE Crane and LE and TE trolleys. LE/TE storage is not shown. Spars are loaded into the spar loader using the crane

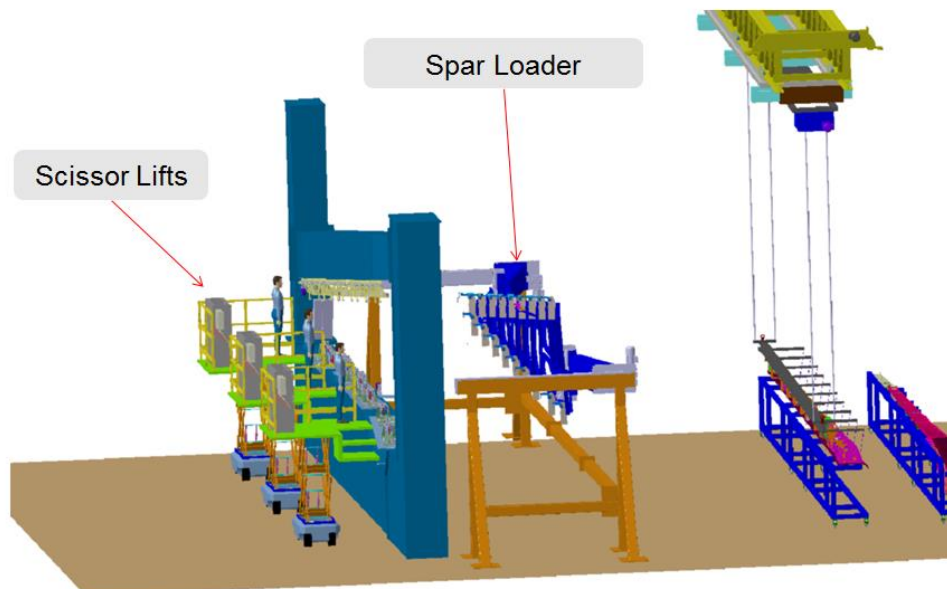


Figure 110. Overview of spar loader and scissor lifts (Cell 1 Staging) for cell 1. The Spar loader indexes the spars to the fixture simultaneously. Scissor lifts provide platforms for operators

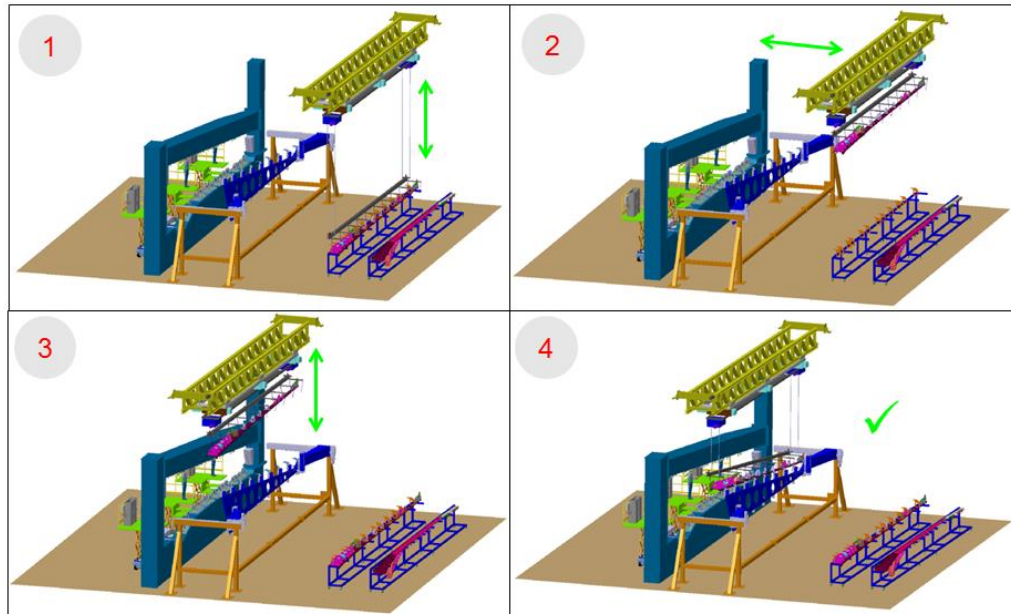


Figure 111. Major process operations of cell 1 to load LE and TE spars to MAF. Spars are collected sequentially by one crane (1) lifted and traversed to the spar loader (2) and lowered into place (3). Each spar is clamped in place in the spar loader (4)

7.5.2 Cell 2 – Rib Drilling

Rib drilling joins the spars and with a series of metallic ribs which form the structure of the wing. PPS DSM for rib drilling presented in Figure 113. Many interactions govern the System DSM for rib drilling which is due to the operators having to use multiple pieces of equipment for rib assembly. This is owing to the use of the original rib assembly processes set in Constraints. Note that rib drilling and fastening is organised into modules. Modules are added along with extra operators for ramp-up. This function was defined in the AD process. An overview of major tooling equipment is presented in Figure 112. Rib cassettes are delivered to the relevant location in the cell for assembly. Rib cassettes contain banks of ribs which are grouped according to size and time to assemble i.e. one cassette contains ribs 2-3 which are the large root end ribs, one cassette contain ribs 4-5, mid ribs are smaller and are grouped 6-9 and so on. Operators use a mechanism built into the rib cassettes to manually load the ribs. Thus reducing the number of operators needed to handle the root end ribs. The rib cassettes have a mechanism which indexes the rib into alignment with the spar rib posts (Figure 114). Ribs are then clamped in place and drilled conventionally.

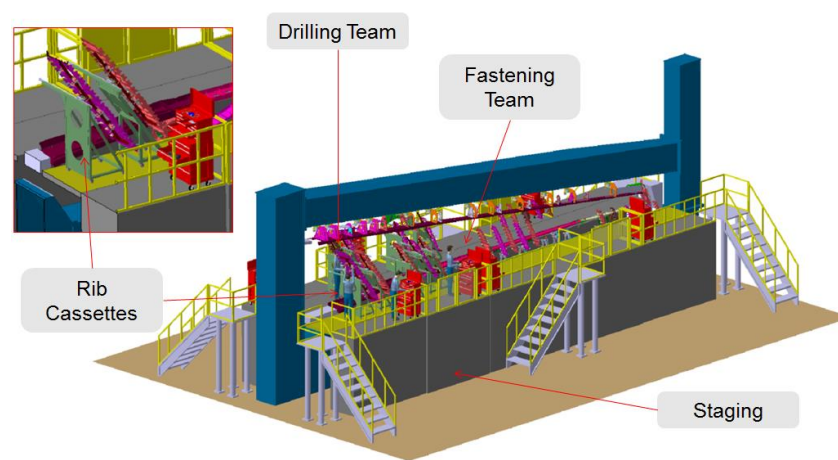


Figure 112. Overview of major assembly tooling systems for Cell 2 – Rib Drilling

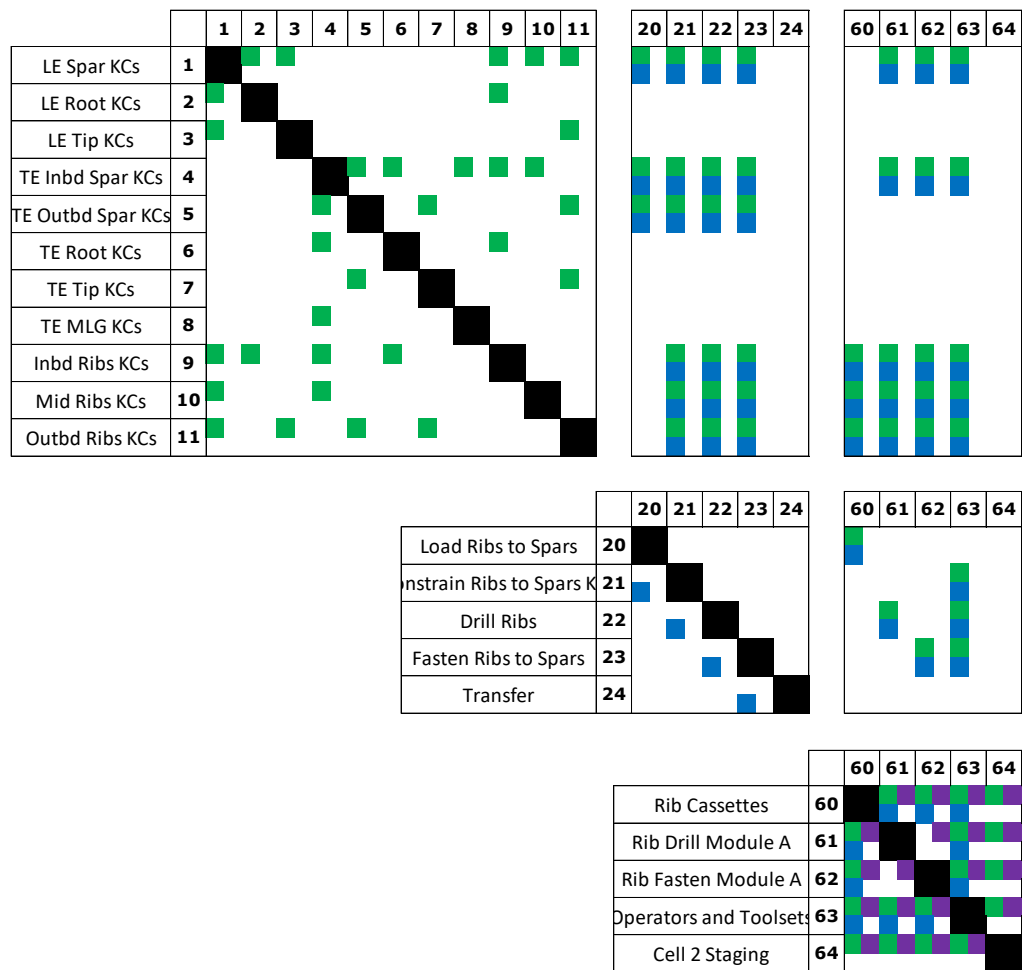


Figure 113. PPS DSM for Cell 2

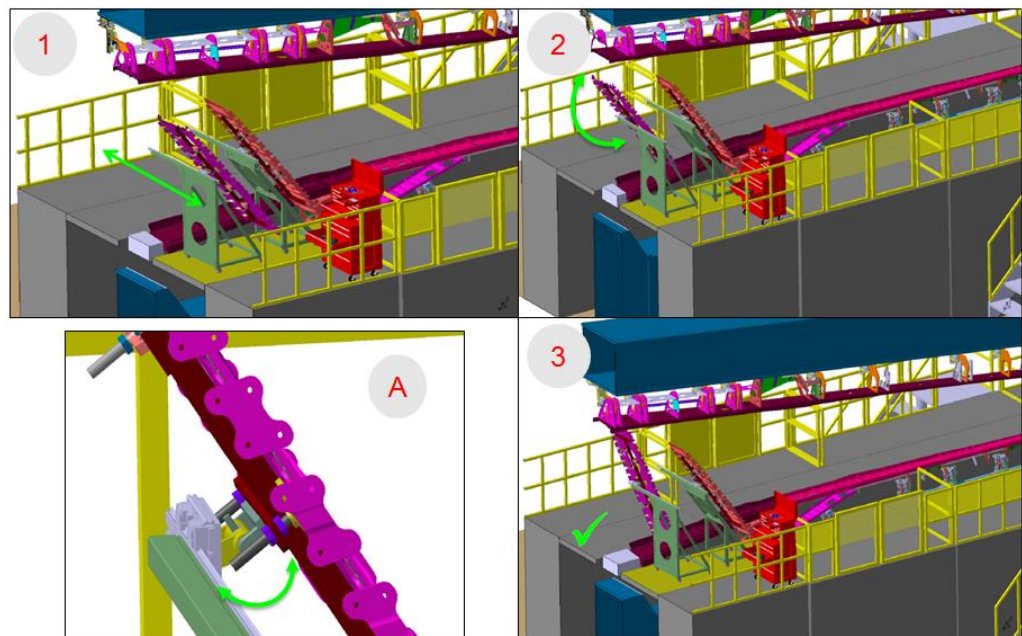


Figure 114. Rib Cassette is shown for ribs 2-3. Rib Cassette has ribs clamped and ready for fitment to spars. Rib is indexed manually by the operator into alignment with the spars (1). A bearing with stops (A) allows the rib to rotate into position to interface the rib web with spar rib post (2). The rib is then clamped using the drill bars prescribed in the current process (3).

7.5.3 Cell 3 – Locate Covers

Cell 3 provides function for temporary fastening of the covers. Dedicated cranes and frames load covers and constrain position while operators fix the cover in place using temporary fasteners prior to drilling. Figure 116 presents an annotated overview of cell equipment. The PPS DSM presented in Figure 115 is used for 3D design of the cover location cell. The product DSM now has the complete set of elements for the wing. The design is a relatively simple system owing to AD process which allows the designer to separate the major assembly processes into independent DPs. Maintaining consistency with higher level FR-DPs in 3D design ensures physical modules are independent and thus exhibit minimal interactions with other modules. This independence provides the scalability capability where capacity increase is achieved by adding labour which does not require new system equipment. Figure 117 presents the process for cover loading. The frames use suction cups and safety clamps to hold the covers, a method commonly used in automotive BiW production. A crane lifts the cover into place for location and temporary fastening. Each cover is located via ‘cup-and-cone’ method at root and tip ends; detailed in Figure 118.

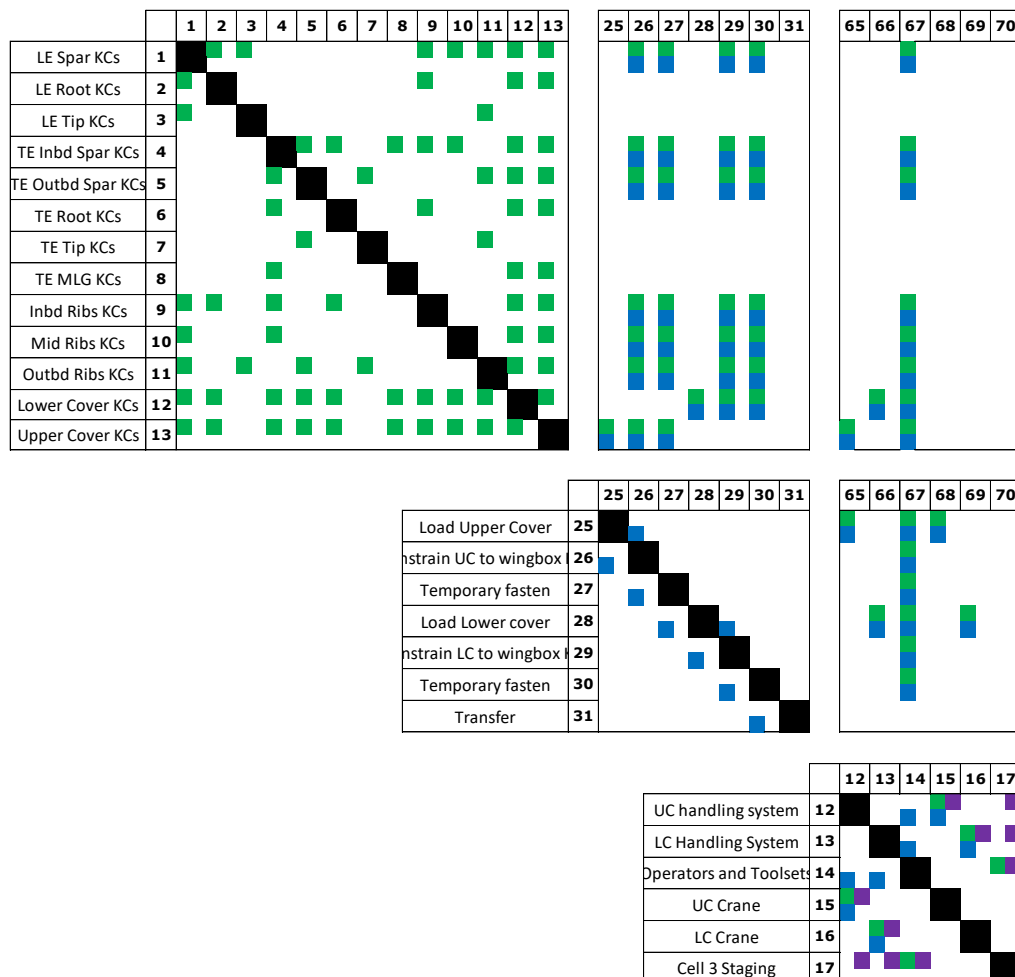


Figure 115. PPS DSM for Cell 3 – Locate Covers

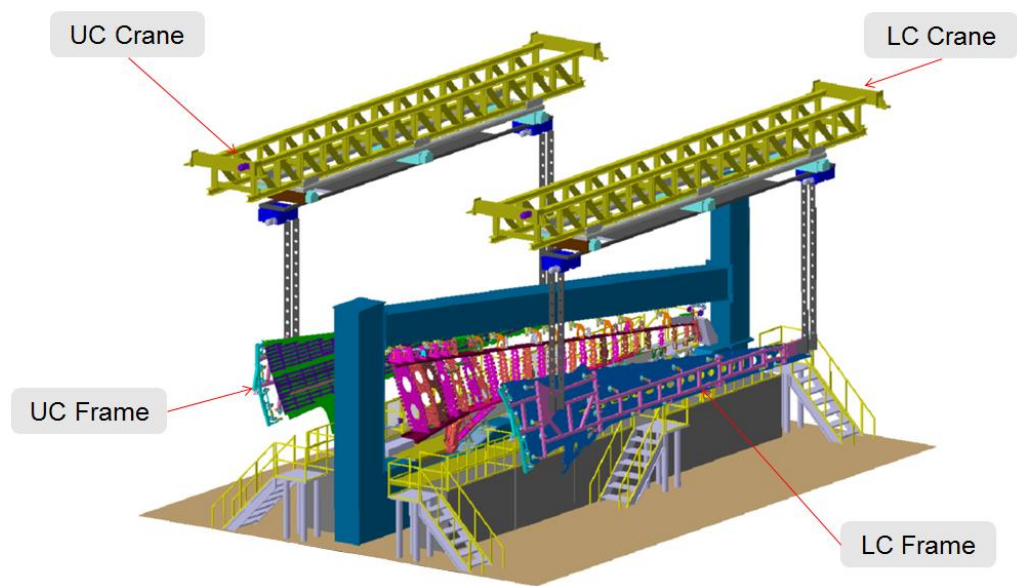


Figure 116. Overview of major tooling equipment used for skin location

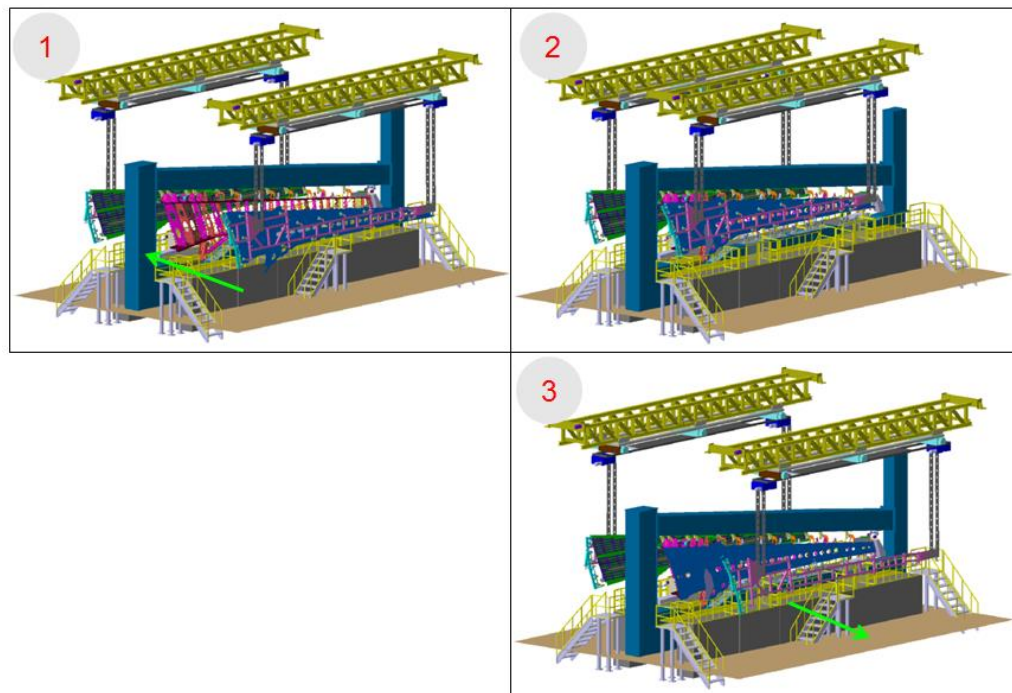


Figure 117. Process for loading lower cover. Lower cover is collected from a storage rack using the LC frame and indexed to the wingbox fixture (1). Tooling pins for root and tip ends of the cover locate in tapered holes on the wingbox fixture (2). Wing cover is tacked in place by operators then crane moves back to start position (3). Process is repeated for upper cover.

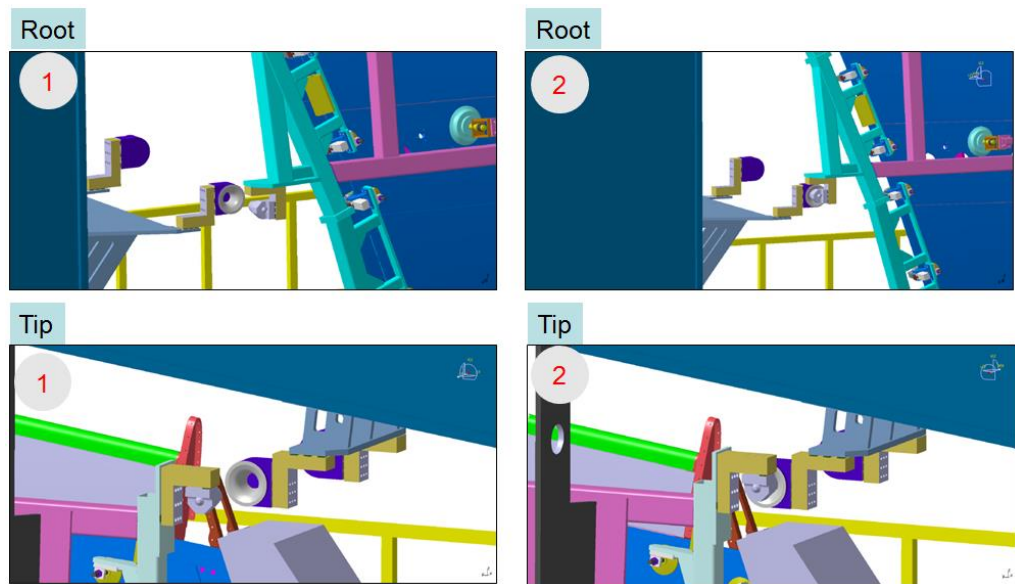


Figure 118. Working principles of cover location tooling for root and tip. 'Cup-and-cone' is used to locate the covers in the correct position for temporary fastening prior to drilling. The cups attached to the cover frames are indexed with the crane (1) and located in the cones attached to the MAF (2). Shims provide adjustability which are used in commissioning to set positions to compensate for tolerance stack-up.

7.5.4 Cell 4 – Drill Covers

Cell 4 uses mobile robotic platforms to drill the upper and lower covers. The drilling is reconfigurable owing to the robotic arm which can be reprogrammed. The cell rate is scaled up by adding additional robot drilling platforms which reduces the cycle time of the cell. The cell embodies the requirements for reconfigurability specified in the AD decomposition. The independence of the mobile robot is crucial to ramp-up because extra robots can be added to the cell without extensive modification. This means the reconfiguration time is kept to a minimum. Long reconfiguration times cause orders to build, leading to backlog. The PPS DSM presented in Figure 119 supports the design team in the physical integration of the cell. Prominent to the design are the proximity between the robot and platform and the MAF. As well as the drilling end effector to spar tooling to avoid skin to spar drilling tooling clash. Note the interaction between the robot and MAF is mapped in the factory DSM presented in Figure 107. Figure 120 presents an overview of cell 4. The mobile robot platform performs the drilling operations for both covers. At rate 40 only one robot is required. Robot platforms are added to increase rate. The access platform is used by operators for service and maintenance. Mobile robot platforms such as the ElectroImpact platform presented in Figure 121 are commercially available and used on in-production aircraft but are not yet used for reconfiguration. This is perhaps due to mobile robotic platforms being a recent development and no new high-rate production aircraft due until 2025. However, mobility is cited as key enabler to reconfigurable systems (Rösiö 2012; Rösiö & Säfssten 2013).

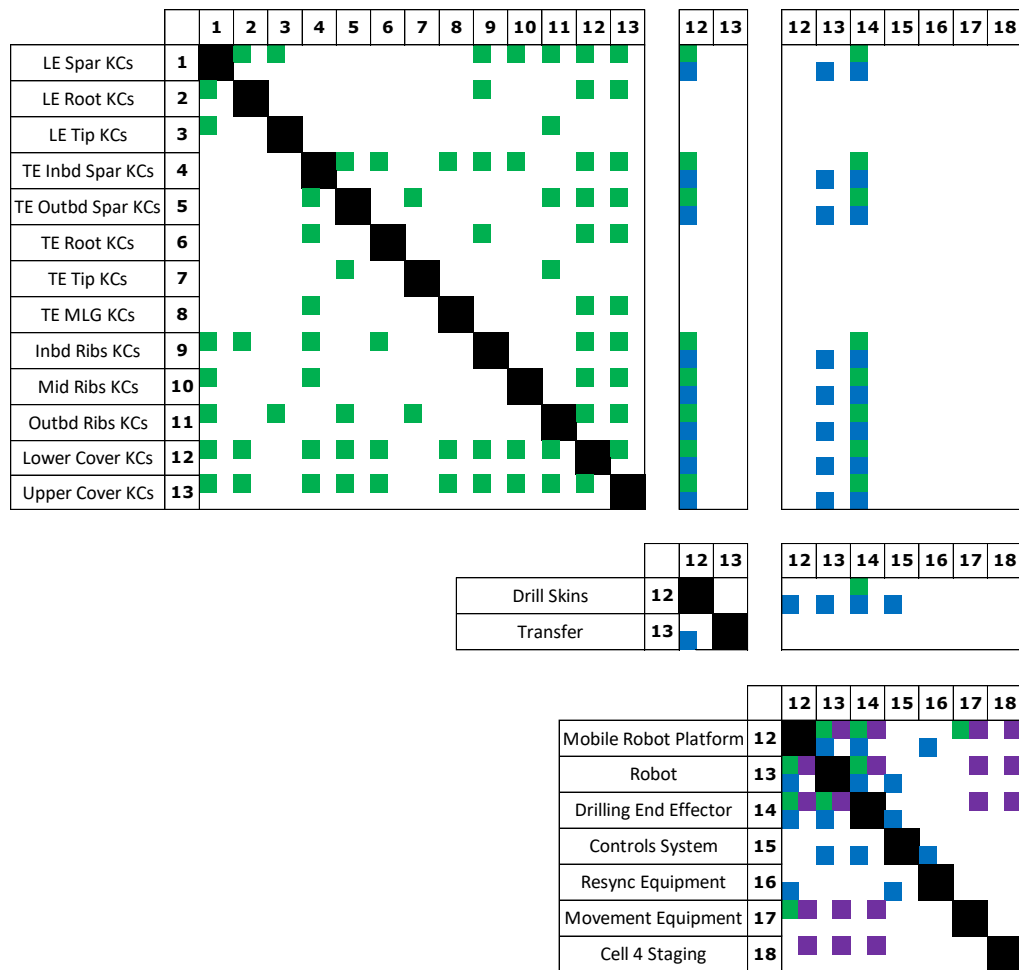


Figure 119. PPS DSM for cell 4 – Drill Covers

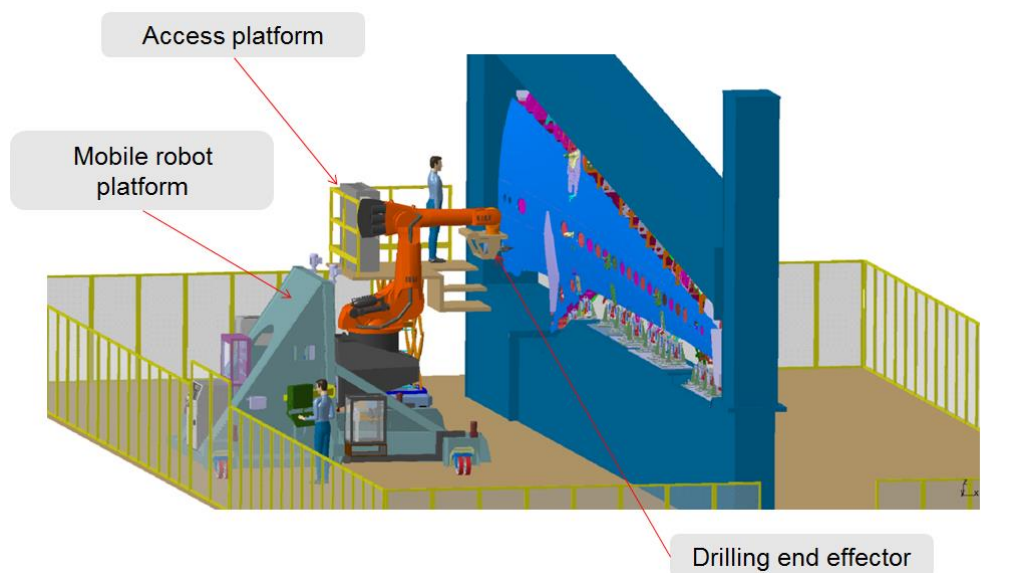


Figure 120. Overview of Cell 4 – Drill Covers



Figure 121. ElectroImpact mobile robot which could be used for reconfigurable assembly (Gray et al. 2013)

7.5.5 Cell 5

Cell 5 removes covers for deburr along with the wingbox after drilling. The Cell overview is presented in Figure 122. Each cover has a dedicated crane, frame and deburr station for simultaneous deburr. Covers are located in Deburr frames which are transferred to cell 6 and 7 after clean-up. Ramp-up is achieved by adding labour owing to the independent functions specified in AD decomposition.

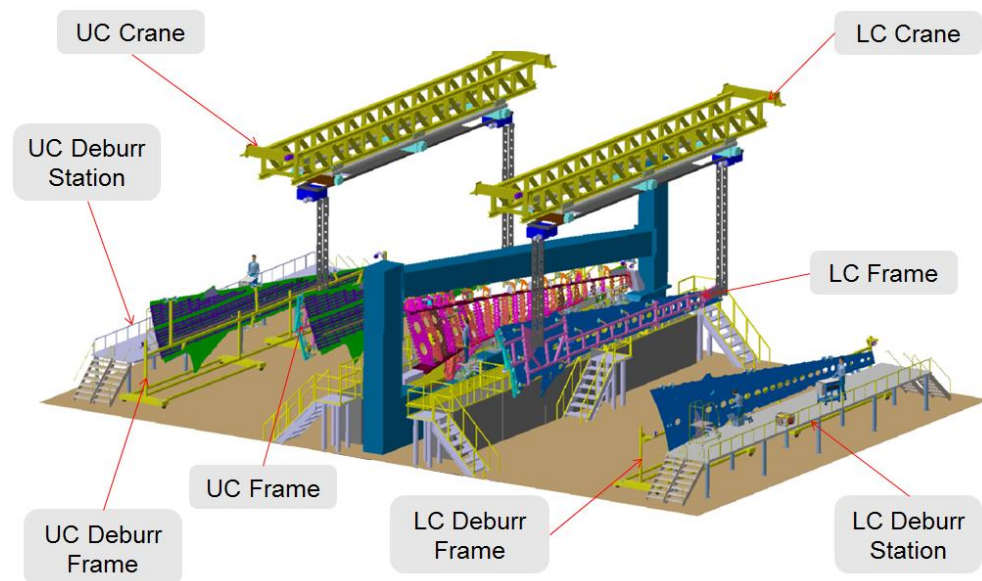


Figure 122. Overview of Cell 5 – Deburr

The PPS DSM is presented in Figure 123. The DSM informs interface design between deburr frames and lifting frames. Interaction between lift frames, deburr frames and deburr stations is also critical to design to ensure systems function correctly and keep process times to a minimum. Factory DSM is used for visualising interactions between cell 5, 6 and 7 where deburr frames are transferred to fastening cells which must also be compatible. Figure 124 presents detailed images of the deburr cell. The deburr frames locate the cover panels using the same cup-and-cone method for repeatability and reduction of design time. Simultaneous deburr of upper cover, lower cover and wingbox is down to specifying independent requirements in AD decomposition.

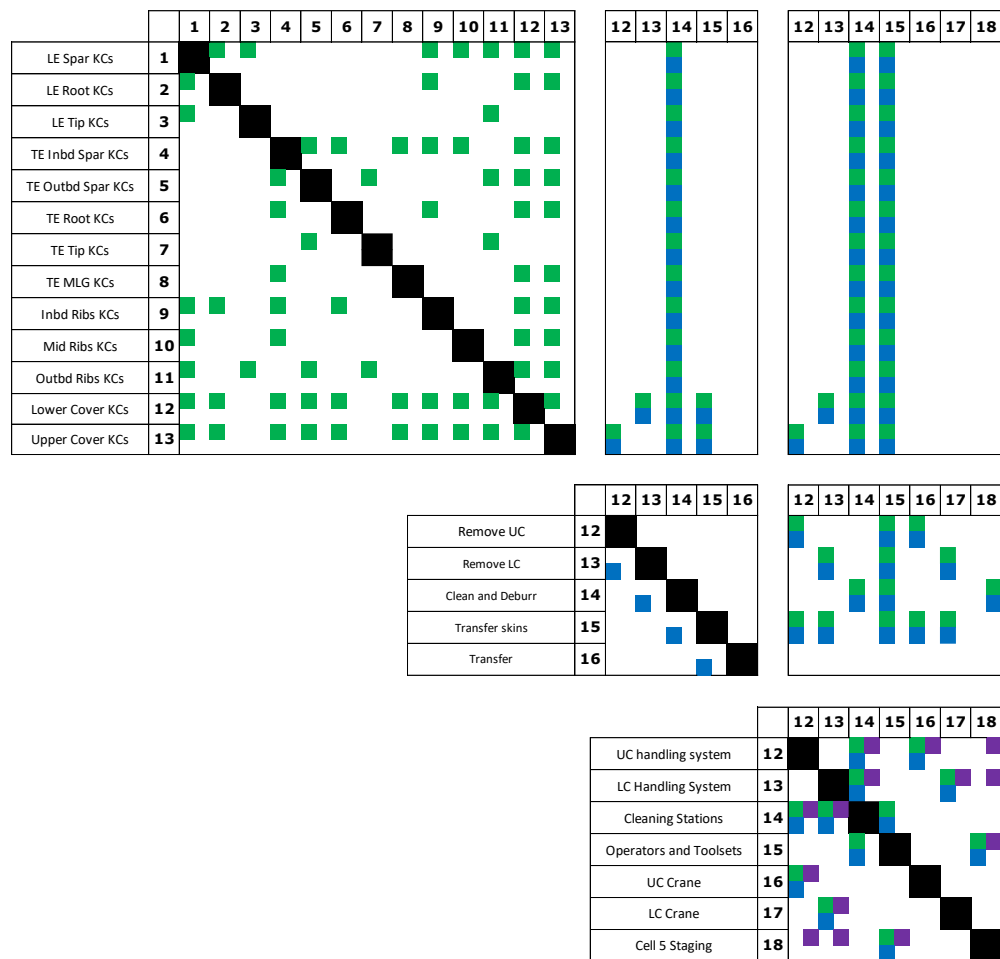


Figure 123. PPS DSM for Cell 5

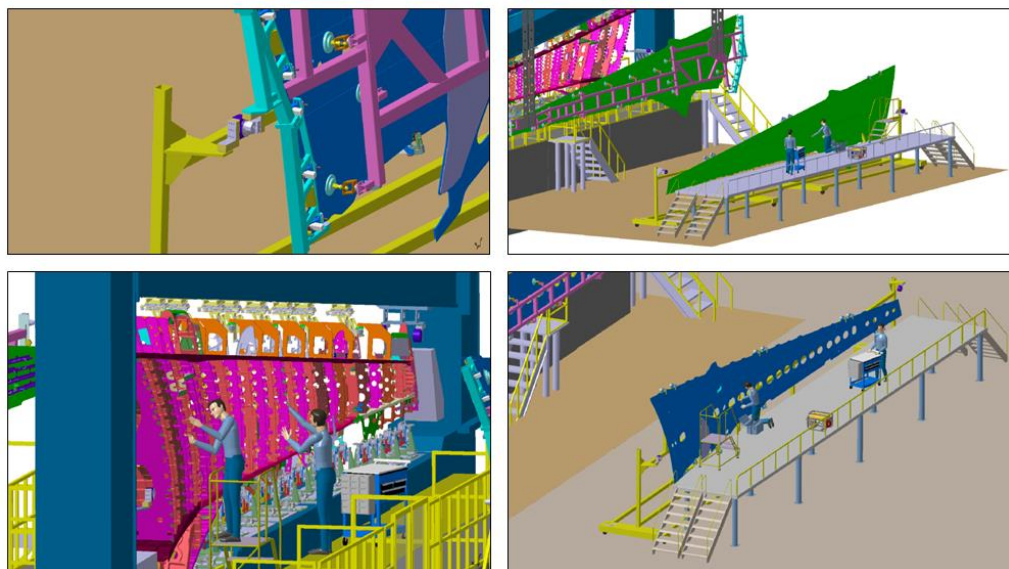


Figure 124. (Clockwise from top-left) Deburr frame uses same location method and safety clamps to hold cover; Deburr station gives access to all areas of cover for cleaning; deburr is carried out manually; operators clean wingbox while covers are cleaned

7.5.6 Cell 6 – Lower Cover Fastening

After deburr, the lower cover is fastened to the wingbox in cell 6. The cell is a simple layout dedicated to lower cover fastening only. An overview is presented in Figure 125 and PPS DSM is presented in Figure 126. Figure 127 presents the process to load and fasten cover which is the same process used today. Ramp-up is achieved by adding operators and dividing fastening along the length of the wing.

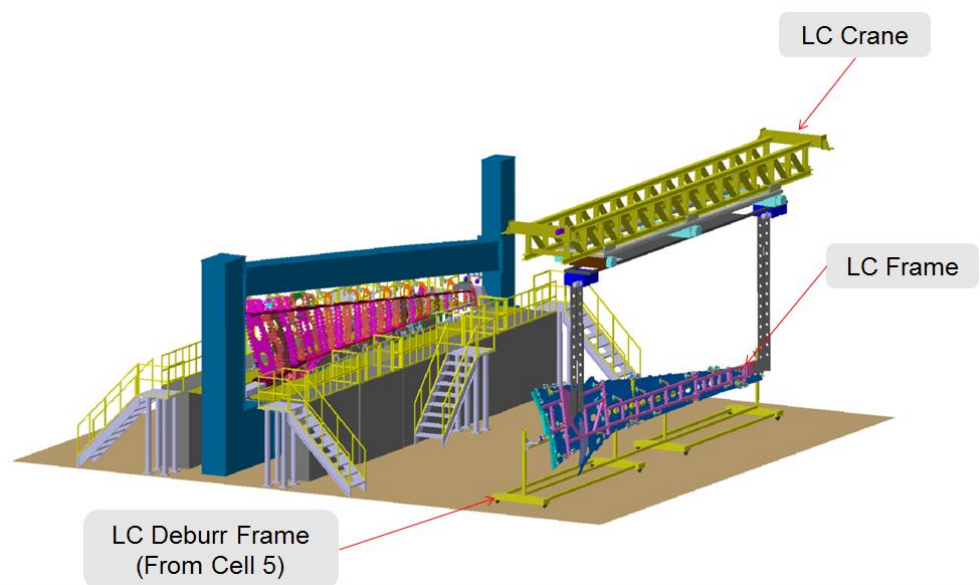


Figure 125. Overview of cell 5 – Lower Cover Fastening

		1	2	3	4	5	6	7	8	9	10	11	12	13		12	13	14		12	13	14
LE Spar KCs	1																					
LE Root KCs	2																					
LE Tip KCs	3																					
TE Inbd Spar KCs	4																					
TE Outbd Spar KCs	5																					
TE Root KCs	6																					
TE Tip KCs	7																					
TE MLG KCs	8																					
Inbd Ribs KCs	9																					
Mid Ribs KCs	10																					
Outbd Ribs KCs	11																					
Lower Cover KCs	12																					
Upper Cover KCs	13																					

		12	13	14		12	13	14
Position LC	12							
Fasten LC	13							
Transfer	14							

		12	13	14		12	13	14
LC Handling System	12							
Operators and Toolsets	13							
Cell 6 Staging	14							

Figure 126. PPS DSM for cell 6 – Lower Cover Fastening

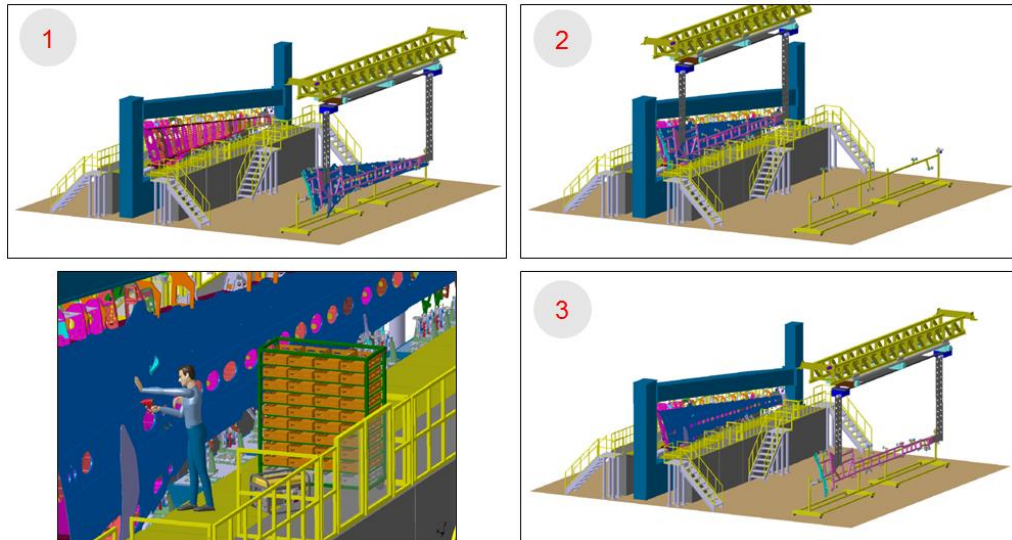


Figure 127. Crane collects lower cover from deburr frame (1) and locates on wingbox (2) then retracts. Cover is manually fastened (lower-left)

7.5.7 Cell 7 – Upper Cover Fastening

The final cell is for fastening the upper cover to the wingbox. Cell 7 is dedicated upper cover fastening only and ramp-up is achieved by adding labour. Cell 7 is similar in design to cell 6. PPS DSM presented in Figure 128 is identical to cell 6 other than domain interactions for fastening the upper cover. An overview of the cell is presented in Figure 129 and uses the same process for loading and fastening as cell 6. Figure 130 presents a detailed image of an operator inside the lower cover porthole to fasten the cover. This is the same as the fastening process used currently.

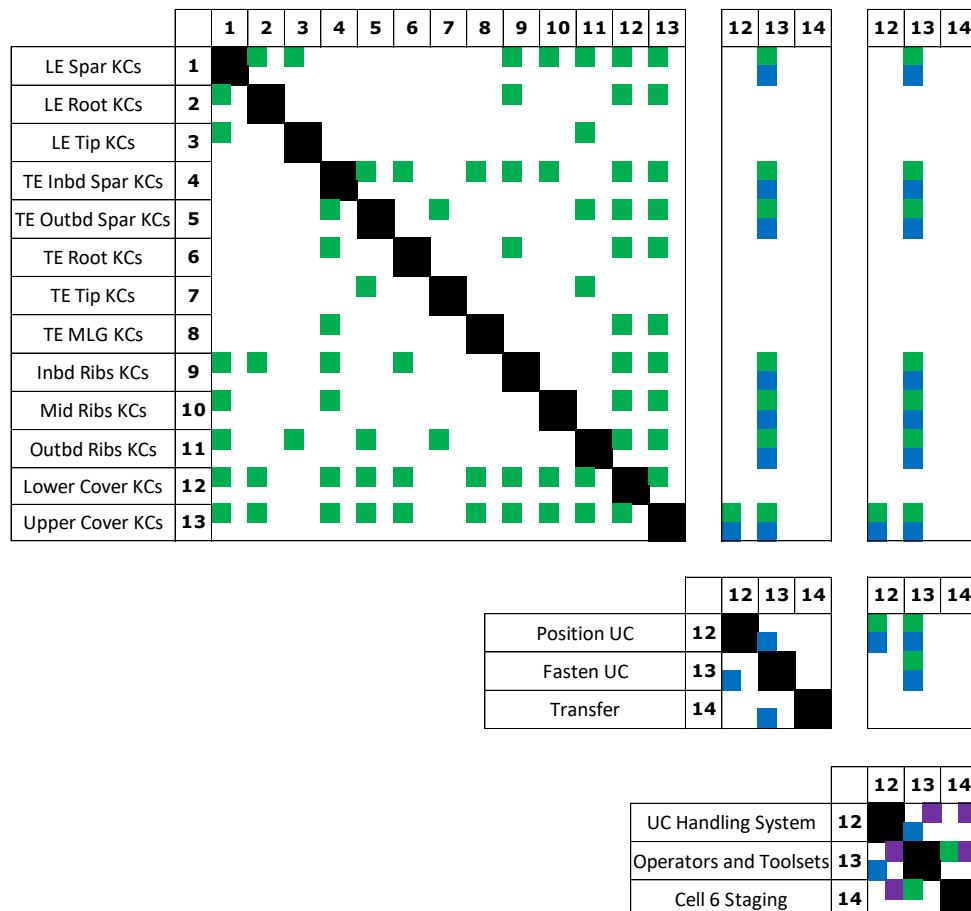


Figure 128. PPS DSM for cell 7 – Upper Cover Fastening

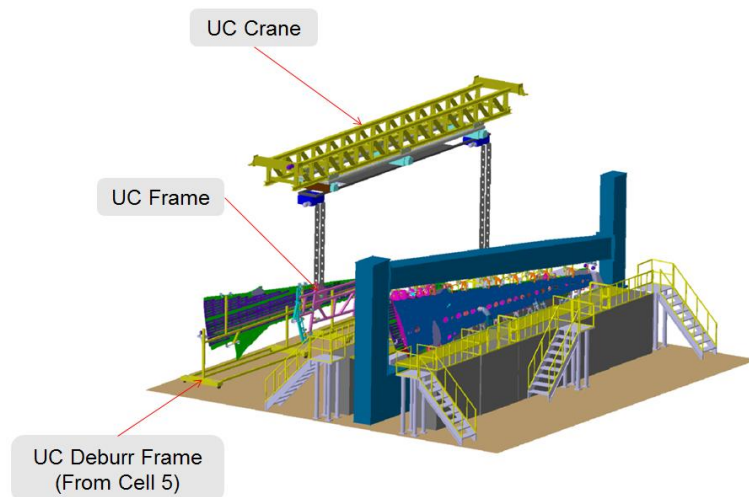


Figure 129. Overview of cell 7 – Upper Cover Fastening



Figure 130. Access for fastening upper cover is through portholes in lower cover

7.5.8 Summary

A virtual A320 RAS design is created by using DSMs to design 3D models. The DM uses DSMs to build the practical architecture of the system which physically embodies the DPs. DSM interactions help visualisation and guide design to conceive tooling designs that are consistent with requirements. A 3D design consistent with DSM ensures the system will satisfy functional requirements. Parts of the assembly system are scalable and customisable in areas predetermined by AD while other parts remain fixed. This provides functions to increase rate by incremental change in structure which remains cost-effective by avoiding excess flexibility or duplicating entire production lines. The RAS designs can proceed to further development and implementation. Designs are used by other parts of the Airbus organisation such as supply chain setup and factory management. At Airbus work is typically broken down into work packages and assigned to stakeholders who manage the progress. Future development should refer to the AD decomposition and DSMs for consistency with requirements and Customer Needs.

7.6 Reconfiguration Modelling

Reconfiguration modelling section of the DM is presented for the A320 RAS. Reconfiguration modelling follows the same principles outlined in Section 6.7. Reconfigurations are modelled by firstly analysing market requirements then adding elements to the factory DSM and mapping new interactions to model change in structure. The new DSMs are used to reconfigure the virtual design which forms the basis of an investment analysis. A ramp-up scenario is modelled for the A320 RAS to demonstrate the process and validate the methodology for industrial use. The data is compared with production metrics of the A320 baseline to quantify capabilities for ramp-up time, production capacity and CapEx. The ramp-up scenario and findings were presented to Airbus project leaders in a formal PDR.

7.6.1 High-Rate Ramp-Up Scenario

The ramp-up scenario was agreed with Airbus UK as part of project deliverables for A320 RAS. The scenario is based on Airbus global forecast for single-aisle aircraft production for the years 2014-2033 (Airbus S.A.S 2014a). The possible newest aircraft earliest entry is 2025 so production will presume a three year production overlap for final order deliveries in 2028. Order forecast takes into account current backlog totalling 19,000 aircraft. Order projection is defined in Section 7.1 and presented in Graph 6. Forecasted orders formed part of the requirements for the RAS. Project launch is considered from 2015, similar to pulse line and the same three-year schedule for factory design, installation and operation launch.

7.6.2 Update DSM

Production using the RAS will be ramped up in increments of 20 up to a maximum of 100 starting with a capacity of 40-per-month. Ramp-up will be as quick as possible to demonstrate reconfiguration capability for comparison with current ramp up time. Requirements for reconfiguration are identified as described in section 6.7. Elements for the reconfiguration are identified and presented in Table 37. The updated DSM for rate 60-per-month is presented in Figure 131. Rates 60, 80 and 100 use identical elements so DSMs for rate 80 and 100 also have the same interactions.

Table 37. Scalable Elements for Ramp-Up	
Scalable Element	Cell No.
TE Trolley	Cell 1
LE Trolley	
MAF	
Rib Drill Equipment	Cell 2
Rib Fasten Equipment	
Operators and Toolsets	Cell 3
Operators and Toolsets	
Mobile Drilling System	Cell 4
Cleaning Stations	Cell 5
Operators and Toolsets	Cell 6
Operators and Toolsets	Cell 7

7.6.3 Update 3D CAD

Factory DSMs are used for each rate increase to model the virtual A320 RAS. By virtue of using the same elements for each ramp-up means the RAS design is scaled up in modular fashion. The DSM changes and corresponding virtual systems are then used to estimate the costs and time to reconfigure as is typical of Airbus today where collaborating engineers use experience and knowhow to estimate the workload and cost. Where the DSM interactions are concerned, some existing elements need modification, e.g. robot platform program needs updating to drill only one cover whereas some interactions between new operators and existing operators need updates to SOIs and work plans.

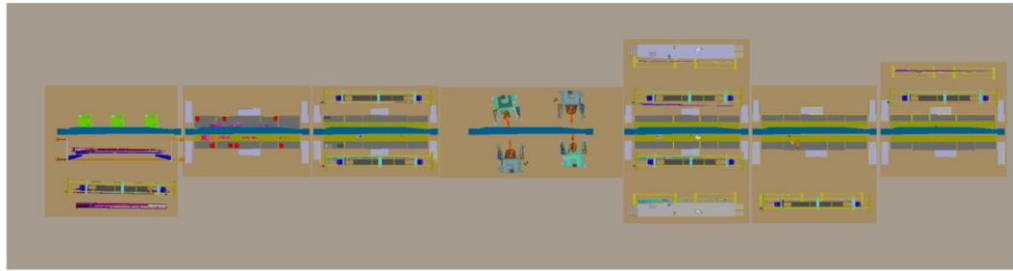


Figure 133. Plan view of factory reconfigured to rate 100 production

7.6.4 Calculate time and cost

As with Section 6.7.8, interactions, new elements and 3D virtual factory form the basis for cost analysis. Analysis is more detailed for A320 RAS because of the more mature processes and data as well as technologies and methods. Some interactions have no cost implication such as proximity interactions so are ignored. Work needed to reconfigure is based on the experience and judgement of operations and manufacturing engineers. The costing process is an experience-based approach based on detailed review of the design followed by a cost-breakdown of the system components. Costs were provided by the Centre for Aerospace Manufacturing which operated as the Airbus Tooling Hub 2009-2015. Costs were later validated by Airbus during design reviews. A complete benchmark can be found in Appendix A. Published metrics for reconfigurable production systems are used adapted for aerospace (Mittal & Jain 2014). A cost model has been developed using Microsoft Excel. The equations used are defined below to arrive at a total CapEx value (Equation 7.2). Capital cost is the material, equipment and manufacturing costs of tooling equipment is typically off-the-shelf items such as sensors or clamps, manufacturing cost is the cost to produce non-standardised parts such as machining for special brackets, fittings or welding for structures (Equation 7.3). Design cost presented in Equation 7.4 is design time and design labour cost. Design time is the total amount of hours needed to design the component. This is estimated by manufacturing engineers and costing experts. Design labour cost is the hourly cost. Installation cost is a similar approach. Installation time is the total amount of hours needed to install the system and installation labour cost is the hourly rate (Equation 7.5). Ramp-up time is the lead time for the equipment which is the time between order and delivery to the factory location (Equation 7.6). Design phase is the time taken to implement and design changes for a reconfiguration; starting with the order sent to the design team up until the design team have finished the necessary work. Installation phase is the time between receiving the new equipment to having the equipment installed and in working order. A delay allowance is added at the discretion of management to cover unexpected delays. Design phase is the number of days needed to complete the design changes and is calculated by dividing the total number of design hours by the number of designers and daily shift time (Equation 7.7). Installation time is the total number of hours needed to install divided by the resource available which is the workforce number of operators and daily shift time (Equation 7.8). Installation phase and design phase are of course subject to internal business constraints.

$$\text{Total Cost (£)} = \text{Capital Cost (£)} + \text{Design Cost (£)} + \text{Installation Cost (£)} \quad (7.2)$$

$$\begin{aligned} \text{Capital Cost (£)} = & \text{Material Cost (£)} + \text{Equipment Cost (£)} \\ & + \text{Manufacturing Cost (£)} \end{aligned} \quad (7.3)$$

$$\text{Design Cost (£)} = \text{Design time (man – hrs)} \times \text{Design Labour Cost (£/hr)} \quad (7.4)$$

$$\begin{aligned} \text{Installation Cost (£)} \\ = \text{Installation time (man – hrs)} \\ \times \text{Installation Labour cost (£/hr)} \end{aligned} \quad (7.5)$$

$$\begin{aligned} \text{Ramp – up Time (Days)} \\ = \text{Lead time (days)} + \text{Design Phase (Days)} \\ + \text{Installation Phase (Days)} + \text{Delay allowance (Days)} \end{aligned} \quad (7.6)$$

$$\text{Design Phase (Days)} = \frac{\text{Design Time (man – hrs)}}{\text{Shift time (hrs)} \times \text{no. of designers}} \quad (7.7)$$

$$\text{Installation Phase (Days)} = \frac{\text{Installation Time (man – hrs)}}{\text{Shift Time (hrs)} \times \text{no. of workforce}} \quad (7.8)$$

The equations were modelled in the spreadsheet to calculate the time and costs to reconfigure for each rate increase. Figure 134 presents an image of the model for rate 40. The spreadsheet calculates ramp-up time from the hours estimated for design and installation. The equations were calculated for each DSM element of each cell. The more complex elements such as the fixture were broken down into BOMs for materials and off-the-shelf equipment and used for more informed estimate of costs.

		Design Time (hrs)	Manufac- ture Lead Time (working days)	Installati- on Time (man- hours)	No. of	Capital cost per	Design Cost	Total Capital cost	Installati- on Cost		ramp up time (days)	ramp up time (months)	BOM	
Cell 1	TE/LE Crane	500	50	5000	1	£750,000	£25,000	£750,000	£250,000	£17,143,000	£1,025,000	81	4	
	TE Trolley	100	50	80	10	£20,000	£5,000	£200,000	£4,000		£209,000	51	3	
	LE Trolley	100	50	80	10	£20,000	£5,000	£200,000	£4,000		£209,000	51	3	
	Spar loading automation	5000	50	2000	1	£400,000	£250,000	£400,000	£100,000		£750,000	113	6	TE Trolley
	MAF	20000	260	10000	10	£1,145,000	£1,000,000	£11,450,000	£500,000		£12,950,000	520	26	Pickup pads
Cell 2	Cell 1 Staging	5000	120	5000	3	£500,000	£250,000	£1,500,000	£250,000		£2,000,000	198	10	Castor Wheels
	Rib Cassettes	500	40	100	5	£20,000	£25,000	£100,000	£5,000	£5,480,000	£130,000	46	2	Box Section (15000mmx100mmx100mmx5mm)
	Rib Drill Module	20000	100	5000	1	£500,000	£1,000,000	£500,000	£250,000		£1,750,000	334	17	
	Rib Fasten Module	20000	100	5000	1	£500,000	£1,000,000	£500,000	£250,000		£1,750,000	334	17	
	Operators and Toolsets	2000	80	5000	1	£500,000	£100,000	£500,000	£250,000		£850,000	127	6	Box Section (600mmx100mmx100mmx5mm)
Cell 3	Cell 2 Staging	5000	120	5000	1	£500,000	£250,000	£500,000	£250,000		£1,000,000	198	10	Box Section (675mmx100mmx100mmx5mm)
	UC handling system	2000	50	2000	1	£400,000	£100,000	£400,000	£100,000	£5,100,000	£600,000	81	4	Box Section (400mmx100mmx100mmx5mm)
	LC Handling System	2000	50	2000	1	£400,000	£100,000	£400,000	£100,000		£600,000	81	4	
	Operators and Toolsets	2000	80	5000	1	£500,000	£100,000	£500,000	£250,000		£850,000	127	6	
	UC Crane	500	40	5000	1	£750,000	£25,000	£750,000	£250,000		£1,025,000	71	4	LE Trolley
Cell 4	LC Crane	500	40	5000	1	£750,000	£25,000	£750,000	£250,000		£1,025,000	71	4	Pickup pads
	Cell 3 Staging	5000	120	5000	1	£500,000	£250,000	£500,000	£250,000		£1,000,000	198	10	Castor Wheels
	Mobile Drilling System	40000	120	10000	1	£10,000,000	£2,000,000	£10,000,000	£500,000	£12,500,000	£12,500,000	589	29	Box Section (15000mmx100mmx100mmx5mm)
	UC handling system	2000	50	2000	1	£400,000	£100,000	£400,000	£100,000	£6,850,000	£600,000	81	4	Box Section (600mmx100mmx100mmx5mm)
	LC Handling System	2000	50	2000	1	£400,000	£100,000	£400,000	£100,000		£600,000	81	4	Box Section (675mmx100mmx100mmx5mm)
Cell 5	Cleaning Stations	1000	80	5000	1	£500,000	£50,000	£500,000	£250,000		£800,000	116	6	Box Section (400mmx100mmx100mmx5mm)
	Operators and Toolsets	2000	80	5000	1	£500,000	£100,000	£500,000	£250,000		£850,000	127	6	
	UC Crane	500	40	5000	1	£750,000	£25,000	£750,000	£250,000		£1,025,000	71	4	Linear Rail and motor system
	LC Crane	500	40	5000	1	£750,000	£25,000	£750,000	£250,000		£1,025,000	71	4	Clamp Assembly
	UC Frame	2500	40	2000	1	£250,000	£125,000	£250,000	£100,000		£475,000	76	4	
Cell 6	LC Frame	2500	40	2000	1	£250,000	£125,000	£250,000	£100,000		£475,000	76	4	
	Cell 5 Staging	5000	120	5000	1	£500,000	£250,000	£500,000	£250,000		£1,000,000	198	10	Pins
	LC Handling System	2000	50	2000	1	£400,000	£100,000	£400,000	£100,000	£3,475,000	£600,000	81	4	Frame
	Operators and Toolsets	2000	80	5000	1	£500,000	£100,000	£500,000	£250,000		£850,000	127	6	Slide Assembly A
	LC Crane	500	40	5000	1	£750,000	£25,000	£750,000	£250,000		£1,025,000	71	4	
Cell 7	Staging	5000	120	5000	1	£500,000	£250,000	£500,000	£250,000		£1,000,000	198	10	Motor A
	UC handling system	2000	50	2000	1	£400,000	£100,000	£400,000	£100,000		£600,000	81	4	Slide Assembly B
	Operators and Toolsets	2000	80	5000	1	£500,000	£100,000	£500,000	£250,000		£850,000	127	6	
	UC Crane	500	40	5000	1	£750,000	£25,000	£750,000	£250,000		£1,025,000	71	4	
	Staging	5000	120	5000	1	£500,000	£250,000	£500,000	£250,000	£3,475,000	£1,025,000	198	10	

Figure 134. Excerpt from Excel cost model. Times and cost estimates were provided by a tooling supplier then validated by Airbus

7.7 A320 RAS Case Study Results

This section presents the results of the case study high-rate ramp-up scenario. A320 RAS Reconfiguration Modelling and A320 baseline production are compared for a production run based on Airbus forecasting. Both systems are compared for ramp-up time, CapEx and production rate to draw conclusions on the methodology and contribute to Airbus project deliverables. The outcomes of Airbus design reviews are also presented. Design reviews served to validate costs and technical feasibility of the RAS design and baseline.

7.7.1 Baseline

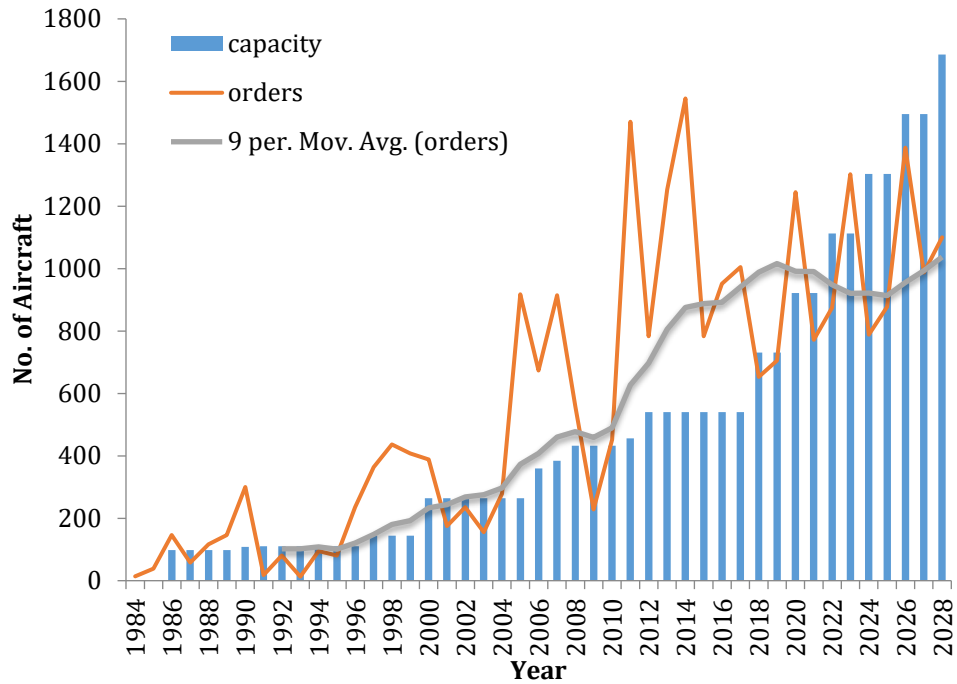
A baseline assembly system based on current A320 production methods is used for comparison with the RAS design to highlight how a RAS might perform compared to conventional assembly methods. The baseline is comparable to the new pulse line but modified for Airbus confidentiality. The system is a non-reconfigurable version of A320 RAS adjusted for representing performance of the new pulse line. The new pulse line uses the same assembly process for the same reasons as RAS which is to avoid certification and use current operators without retraining. Baseline costs are estimated in the same manner using the cost modelling in section 7.6.4 and share much of the RAS design's non-reconfigurable elements. The ramp-up method is by duplication of production lines. Each production line produces a monthly rate of 16 wing pairs. Ramp-up time is 24 months to build a production line based on planned internal milestones of new pulse line.

7.7.2 Ramp-Up

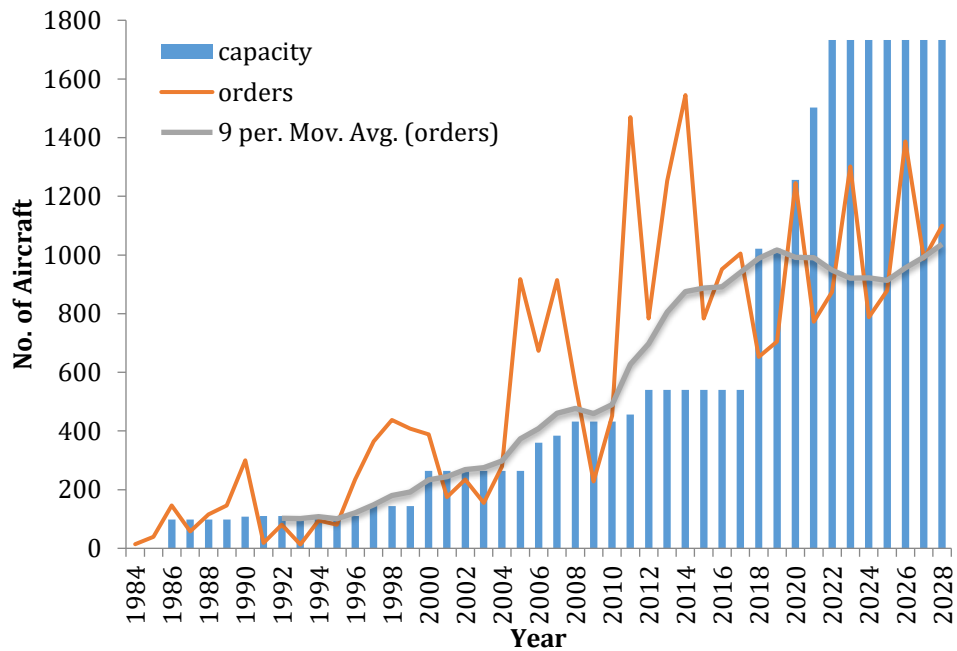
Capacities are added for A320 baseline and RAS for Graph 6 presented in Section 7.1. Graph 7 presents the estimated capacity using the baseline assembly system. Extra production lines provide 191 aircraft-per-year extra capacity every two years. Final production rate in 2028 is 1685-per-year which is a three-fold increase of current production rate. The pulse line method is a marked improvement over the fixtures method with greater capacity increases afforded by the higher production rate of a pulse line. Capacities for RAS of A320 wings is presented in Graph 8. As orders come in, RAS is able to respond to orders and increase in increments of 20 per month each year up to the maximum capacity. Ramp up improvement is 50% decrease in ramp-up time, shortening from 24 months to 12 months. Table 38 presents capacities for each respective assembly system and the percentage increase RAS has over the baseline each year. Excluding the current fixtures (rate 42), the RAS reaches rate 80 in 2021 (1503 aircraft/year) compared to the baseline rate 45 (992 aircraft/year) The RAS reaches rate 100 (1732 aircraft/year) in 2022 whereas the baseline is capable of rate 93 (1113 aircraft/year) in 2022 which is a 36% increase in capacity. Baseline capacity converges just short of 47 aircraft/year in 2028, 7 years after RAS achieves rate 100.

Table 38. Year-on-year capacities for A320 baseline and RAS design with calculated percentage increase

Year	Baseline Capacity	RAS Capacity	% Increase
2018	731	1022	28%
2019	731	1022	28%
2020	922	1255	27%
2021	922	1503	39%
2022	1113	1732	36%
2023	1113	1732	36%
2024	1304	1732	25%
2025	1304	1732	25%
2026	1495	1732	14%
2027	1495	1732	14%
2028	1685	1732	3%



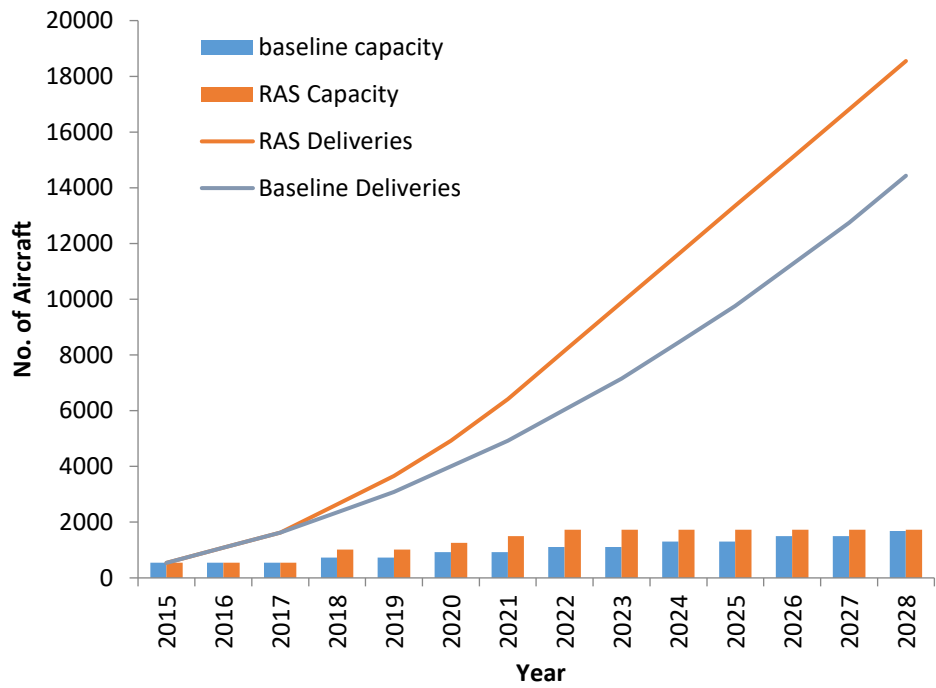
Graph 7. Estimated Capacity using A320 baseline for production of single-aisle aircraft



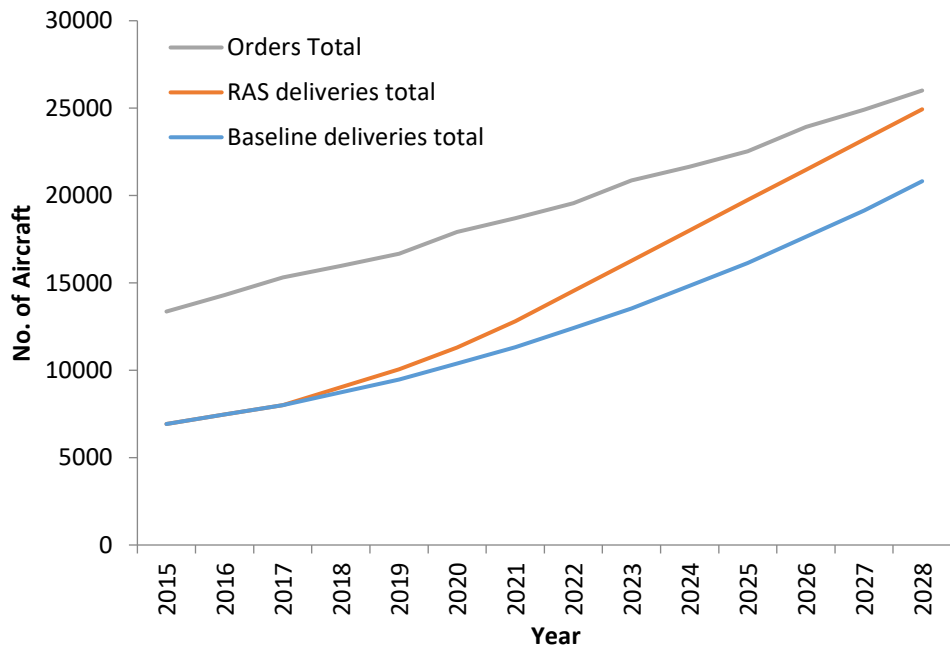
Graph 8. Estimated Capacity using A230 RAS for production of single aisle aircraft

7.7.3 Backlog

Graph 9 presents the total deliveries and capacities over the production duration for the RAS and Baseline Assembly System. The Baseline Assembly System delivers a total of 20818 aircraft in 2028 and the RAS delivers a total of 24933. The increase in ramp-up and production capacity afforded by the RAS leads to a 20% increase in deliveries by 2028. Graph 10 presents the total deliveries of each system and the total order sum for each year. Total backlog for the Baseline Assembly system is 5190 and RAS backlog is 1075. RAS achieves an 80% reduction in backlog compared to Baseline Assembly System.



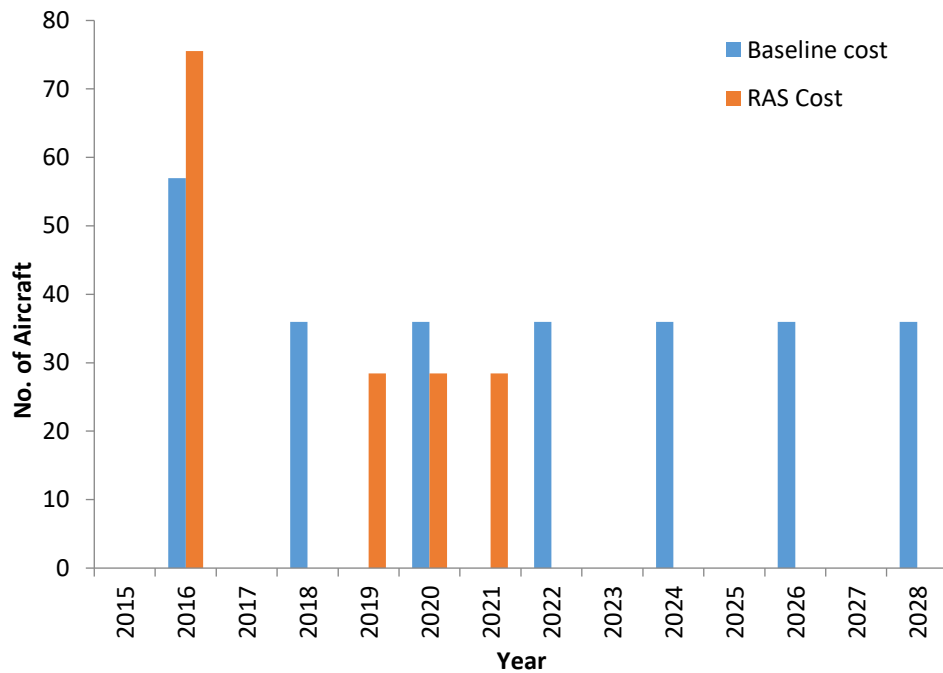
Graph 9. Respective year-on-year deliveries and capacities for RAS and Baseline



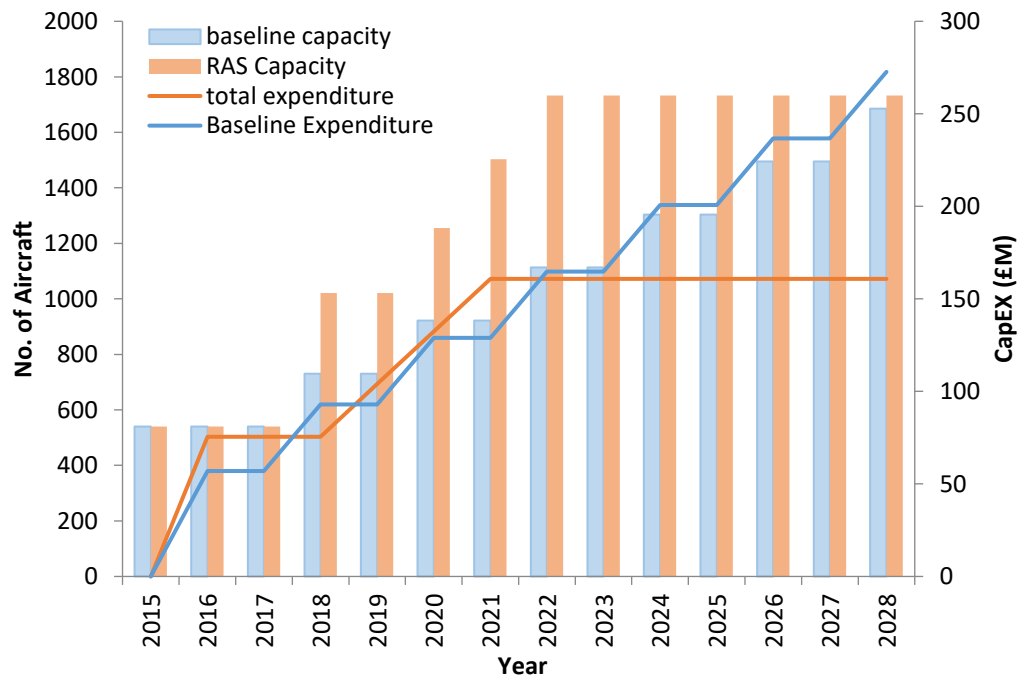
Graph 10. Total deliveries for RAS and Baseline Assembly System and total orders

7.7.4 Cost

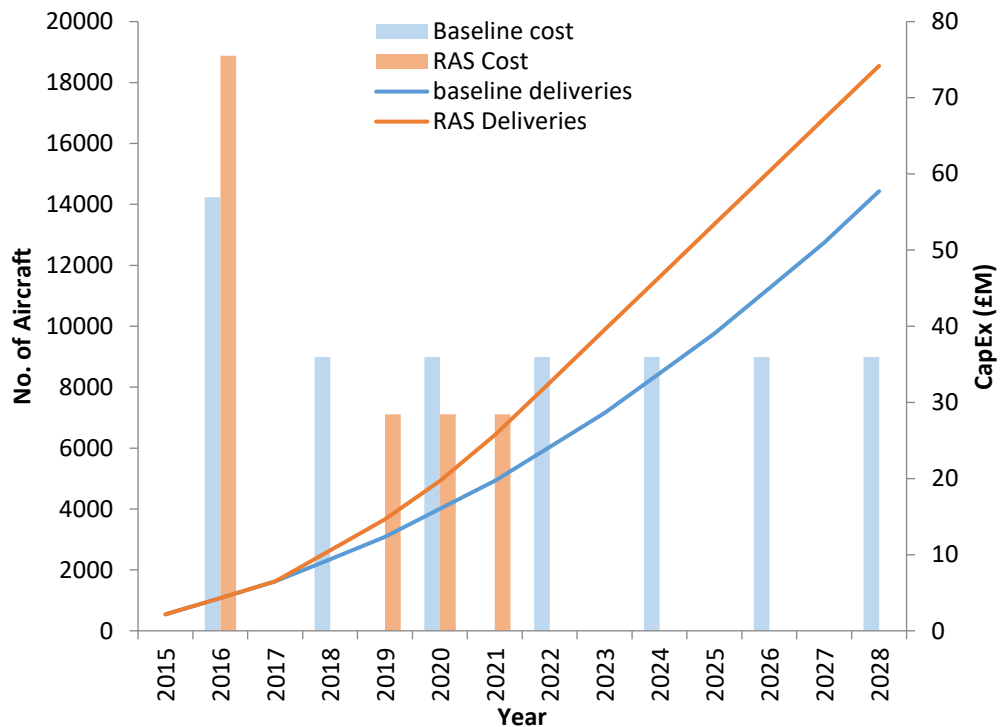
Costs are presented for CapEx for assembly tooling as described in 7.6.4. Yearly CapEx investments for each system are presented in Graph 11. The first investment in 2016 is 33% higher than the Baseline system. By year 2021 RAS investment is 26% higher than Baseline. In year 2028 total CapEx is 41% less for RAS. Graph 12 presents total CapEx and yearly capacities for each system. The baseline system requires continual investment because of order accumulation during slow ramp-up. Yearly CapEx and total deliveries are presented in Graph 13. Slow ramp-up leads to compounded orders, which then requires additional capacity and therefore investment. Additional capacity is subject to same ramp-up constraints and so effect is multiplied and more backlog is accrued.



Graph 11. Yearly CapEx investments for A320 RAS and Baseline Assembly System



Graph 12. Total CapEx and yearly capacities for RAS and Baseline Assembly System



Graph 13. Total Orders and Yearly CapEx for RAS and Baseline Assembly System

7.7.5 Airbus Design Review

Two independent Airbus PDRs were conducted for the RAS design to validate the costs and technical feasibility of the designs. RAS designs were presented along with the cost model and ramp-up times. Airbus PDR reviewers are senior manufacturing engineers. The first PDR was chaired by A. El-Nounu and the second PDR: M. Redman and D. Tomlinson. Descriptions of the reviewer's roles and experience are presented in Table 39.

Table 39. Airbus PDR Participants

Name	Position	Experience Summary
A. El-Nounu	Lead DfA Engineer	- 7 Years Aerospace Manufacturing - Automation Research Engineer - Metrology Research Theme Lead
M. Redman	UK Work-stream leader in Manufacturing R&T specializing in Automation	- 14 Years Automotive Assembly - 8 Years Airbus Automation Specialist - 5 Years in current role
D. Tomlinson	Airbus UK Assembly Tooling Lead	- 30 Years Aircraft Tooling at Airbus Filton - 5 Years in current role

The RAS designs were reviewed cell-by-cell and critiqued according to Airbus protocol which includes working principles, technical feasibility, risks, assumptions, alternatives and accuracy. Outcomes of the PDRs were documented in minutes and are presented in Appendix B. The first PDR found estimations for costs and rates to be reasonable. Queries were made regarding cell 4 ramp-up where adding a mobile robot would incur costs to reconfigure the first robot. This was considered in the design and costs were already allocated which satisfied the query. The PDR found the review to be a fair and logical comparison of two systems with different approaches to ramp-up and found RAS to have faster ramp-up capability which had been factored into the design process.

The second PDR was carried out in the same manner. Overall, the costs and rate estimates were believed to be reasonable and comparable to current production. A number of queries were raised regarding some of the designs which are discussed. The labour content of cell 2 was queried for feasibility at rate 100. Clarification was provided by way

of highlighting that ramp-up of cell 2 allocates 10 months ramp-up time to deploy labour resource which is comparable to current ramp-up. For cell 4, reviewers were satisfied with the scalable principles of adding mobile robotics as well as the cost model which covers the extra design time. A query about safe handling of the covers was raised for cell 5, safety clamps which were included in the AD constraints were pointed out which satisfied safety concerns. Cell 6 and 7 were believed to be technically feasible but next stages should investigate strength of handling frames with FEA studies. Final remarks of the PDR concluded that the RAS design is technically feasible and the reconfigurable line offers greater ramp-up capability over the baseline system for higher initial investment but lower long term costs.

7.7.6 Limitations and Assumptions

Case study results show reductions in ramp-up time and backlog for RAS in comparison to the baseline system. However, these results are not without certain limitations and assumptions. The case study only considers one orders scenario. Whilst this is acceptable for Airbus other scenarios may highlight deficiencies in a broader context. The order scenario was chosen by Airbus to best suit their requirements and the rate 20 increments covers most order possibilities so the system design is still valid. In assembly terms, extra capacity without duplication of production lines is certainly beneficial; particularly so in the case of A320 which has a substantial backlog. The DM produces virtual designs based on translating customer requirements into physical solutions. Ultimately, virtual designs are subject to validation in physical terms as with all virtual modelling. Steps were taken to ensure designs were feasible by conducting PDRs of the system and are believed to be correct. Current Airbus practice is to use CAD to design tools virtually before committing to production. The virtual designs will be subject to Airbus R&T milestones described in section 2.2.2 to ensure designs are robust. Another related factor is the PDR process itself. Despite seniority and experience of the reviewers, expertise is limited to assembly and manufacturing environment. Stakeholders from other departments may find shortcomings when placed in a broader context. This is a common occurrence at Airbus and is usually resolved with collaboration and revision to aspects of the design. This focus on assembly raises other limitations of similar nature. Technical feasibility is dependent on many other aspects of the business such as logistics, supply chain, geographical and political considerations. Work in these areas is part of the ongoing development of aircraft programs. The baseline system and RAS assume equal human resource because this is not normally within the remit of R&T. This issue was raised in the PDR, with similar rates and assembly processes coupled with the higher automation of the RAS human resource is likely to be similar and should not place restriction on system performance. Limitations of the cost estimations must also be highlighted here. Costs are limited to tooling CapEx only which is common practice for Airbus tooling R&T and in line with the specific directive at Airbus to reduce tooling CapEx. While costs are estimates only, steps were taken to independently verify the estimates. The tooling supplier has extensive costing experience which provided this estimates which were then verified in two independent Airbus design reviews. What's more, with a backlog of 6190 aircraft which represents substantial revenue which means costs may not be prohibitive if undervalued. The project aim is focused on ramp-up which is believed to be technically feasible in the design.

7.8 Chapter Summary

The DM is used to produce a RAS which meets Airbus requirements for high-rate and production ramp-up improvement of A320 production. The case study uses an Airbus industrial scenario for the current A320 production which is experiencing a backlog of over 6000 aircraft and a global forecast for single aisle of over 19,000 aircraft. Designs for a RAS are presented along with associated steps of the DM. Reconfigurations of the designs are modelled and used to estimate costs and rates of ramp-up compared to a baseline system comparable to current production. Results of the case study find ramp-up reduction of 50% and an 80% reduction in backlog for the high-rate scenario. The RAS design and baseline were presented in Airbus PDRs for critique on feasibility and accuracy and found to be reasonable.

Chapter 8 Discussion

In Chapter Eight the implications of the research are discussed in wider context. A critique of the DM and case study results evidences the various advantages and limitations. The significance of the DM to the fields of RAS design and aerospace assembly is addressed, including comparison to the literature. The RAS designs are discussed in regard to future assembly systems; particularly for Airbus. The research questions are restated to evaluate the extent that they have been answered by the research. The chapter closes with the research limitations.

8.1 RAS Design

This section explains the significance of the DM to the field of RAS design. The DM provides the means to translate customer requirements to a physical system design – specifying the right level of scalability and customisation in order to be cost-effective. In designing from the outset, the RAS can efficiently change in capacity or functionality to respond to market change. The section is divided into the main features of the methodology and explains the impact each has for future RAS design.

8.1.1 RAS Requirements Framework

The DM contains a requirements capture framework developed specifically for Airbus RAS to capture and combine expertise and system requirements for capacity and functionality. Existing knowledge combined with customer aspirations forms the basis for the AD mapping process. The framework consists of Customer Attributes Gathering and Customer Needs formalisation. Designers use the framework to capture the relevant customer requirements and existing work and combine them to form a set of Customer Needs for ASD.

This framework allows the designer to utilise Airbus expertise by including solutions from previous programs in the design. This improves the requirements definition stage and reduces the likelihood of repeated design effort. Using the requirements framework allows the designers to express requirements for reconfigurability in direct relation to customer needs and the current expertise. Later parts of the methodology map these requirements directly to physical structures thereby satisfying the requirements and embodying the characteristics for reconfigurability.

This is demonstrated in case studies which use the framework to create meaningful system requirements. One example is presented in the first case study RAS for a future aircraft where development is ongoing. The early stage of the aircraft design means information for system design is often conflicted in a trade-off between two aims. Design of the aircraft structures progresses at different rates and change frequently so engineers become the primary source of design information. System design must also consider lessons learnt of previous systems and consider current R&D influence on the system design. This information was captured for NGCW and consolidated using the RAS requirements framework and used to create Customer Needs which were translated into a system design which exhibited use of current solutions and integrated R&D into full-scale designs. In the second case study, workshops are conducted with Airbus engineers to elicit requirements. The global forecast for single-aisle aircraft is discussed and used to create requirements for ramp-up capability. Requirements specification considers Airbus aspirations for greater reconfigurability and automation and review existing pulse line for lessons learnt before formalising customer needs.

Designers use the framework to gather data from various sources to create customer needs and a resource for information to influence design. Aerospace design is conservative for safety which restricts a large amount of potential solutions and innovation because of certification costs. The framework also serves to structure knowledge capture where tacit knowledge is the primary source of design information in aerospace. The information is used by the designer to formulate Customer Needs (part of AD theory - used to create functional requirements) and reference data for design.

The framework is a continuation of existing work on aerospace knowledge (Mas, Menéndez, et al. 2013; Mas et al. 2014). Such knowledge is necessary for design but not mentioned by existing methodologies. Previous RAS design methodologies do not appear to state this step (Al-Zaher et al. 2013; Al-Zaher & ElMaraghy 2014). Frameworks to capture requirements do exist for cellular assembly system design (Manzini et al. 2004). Several methods acknowledge designer knowledge and experience as fundamental but do not give a formal process for using this experience. Perhaps due to academic publication for generic application where it is not possible to consider the unique needs of each organisation. It may also perhaps be in part due to lack of implementation in industrial case studies which have not uncovered this problem. Several researchers stress the significance of tacit knowledge in aerospace and consider knowledge capture but lack details on application to design. A lot of effort is invested in studying the current capabilities, lessons learnt and R&D which is not considered by other methodologies. The industry approach does consider existing knowledge and solutions but in ad-hoc fashion which has led to poor design. Using this framework the designer can capture and compare all the necessary information and provide more accurate foundation for design.

8.1.2 Specifying Scalability and Customisation at Design Outset

The AD method is used to specify independent scalable and customisable requirements in accordance with Koren (1999) ‘...Exactly the capacity needed when needed.’ Designers use the RAS requirements framework to maximise use of design knowledge. AD stresses independent, uncoupled design which is key to enabling rapid change in system structure. The hierarchical approach means requirements are deconstructed to specify scalability and customisation for specific customer needs. This leads to a mixture of flexible and non-flexible subsystems which is more cost-effective than full flexibility.

Both case studies use the framework to specify functional requirements for system reconfigurability which are decomposed into sub-functions which correspond to physical tooling designs which can change in structure to increase capacity or change functionality. AD ensures subsystems for assembly are independent, allowing changes to structure which do not affect other parts of the system. Using AD to state requirements for scalability means equipment that can provide exactly the amount of capacity/scalability is embodied in physical designs. AD is suited to the design of reconfigurable systems for Airbus because of the focus on independence and complimentary use of designer knowledge.

Most work on scalability has focused on optimisation using numerical methods without practical consideration of hardware or industrial use. Some notable papers mention ‘mobility’ which is essentially moving equipment around a factory and using multiple functions but show no practical demonstration of this (equal to RAS characteristics of scalability/customisation/convertibility); (Rösiö 2012; Rösiö & Säfsen 2013). AD can be used to design equipment to have these specific capabilities derived from individual customer needs.

8.1.3 Mapping Requirements to System Designs

AD specifies functional design architecture but not physical architecture. DSMs are used to develop a physical system architecture which is consistent with the AD decomposition. A PPS DSM is constructed through designer interpretation of the Design Matrix and Customer Needs. The designer then specifies interactions between DSM elements to inform 3D design. Interactions are specific to RAS and show practical constraints of the system which guide designers in producing detailed designs for reconfigurable assembly.

The new method uses a systems approach to specify physical components and processes for a complete RAS. DSM of products, processes and system is necessary for RAS design because reconfigurations affect the entire system. Showing the entire system with interdependencies allows designers to note interactions and design interfaces suitable for scalability and customisation. Thus a complete system is designed from the outset to have adjustable capacity and functionality where needed. Using DSMs consistent with the AD

decomposition helps ensure reconfigurable characteristics are physically embodied in the physical system design.

DSMs are used in the first case study to model the machining cell for NGCW. Machining modules are added to increase production rate as are drilling modules. DSMs are used to show spatial proximity, mechanical interactions and process interactions to avoid tooling clashes and machine cooperation. For the second case study, DSM interactions inform designers of connections between elements which are then designed accordingly so that parts of the system can change in structure to increase capacity. For example, this can be seen with the addition of mobile robotics to increase production rate in cell four. The DSMs were used to design the robot systems to be independent of the cell structure so that they can be reconfigured with introduction of additional robot modules for ramp-up.

Previous work focuses on converting AD to single Product DSM only (Guenov & Barker 2005; Tang et al. 2009). A PPS DSM is necessary for RAS design because reconfigurations affect the entire assembly system. Changes to system structure necessitate changes to process and may change how the product is interacted with. Al-Zaher (2014) uses DSMs from a tooling hardware only perspective and does not consider process and spatial interactions which carry associated costs and practical constraints which may render a reconfiguration unfeasible. Al-Zaher (*op. cit.*) also only focuses on tooling changes for model change of a specific vehicle. The new systems approach presented here is applicable for different reconfigurations such as new technologies or changes to the process. Farid (2007) uses interactions but only considered for equipment and not the wider system (product, process) so system changes caused by change in product or process cannot be visualised. Furthermore, the interactions are not used for machine design, layout or practical considerations and so does not constitute RAS design. Interactions are used only for assessing and measuring reconfigurability in an existing system. What's more, the research makes no mention of cost or ramp-up time which is crucial to implementation in industry.

8.1.4 Modelling Reconfigurations

Post 3D Design, the RAS DSM is used to test reconfiguration scenarios. Without plug-and-produce modules, reconfiguring an assembly system incurs some engineering work. A reconfiguration involves adding or modifying equipment to change production rate or model type. This can be represented using the RAS DSM for product, process or system changes.

The DSM model is used to visualise effects of reconfiguration by mapping new system interactions caused by adding or changing system elements. Highlighted changes are used to assess impact of reconfiguration e.g. costs, downtime, system integration. The designer uses the tool to document the work involved to implement the reconfiguration which is used to calculate investment costs and implementation time. Interactions show practical constraints of reconfigurations as well as helping to calculate costs to create new interactions. The costs and time of reconfiguration can be calculated by using the DSM and 3D model to estimate the work needed to modify or add each element i.e. add a new robot and end effector or new process. Method allows designer to assess many different changes i.e. reconfigurations. This allows the designer to see which reconfigurations have the biggest impact with least disruption, minimising costs and downtime.

Understanding system interactions is necessary for RAS design because reconfigurations affect the entire system. The method allows designers to visualise effects of changes to the system for reconfigurations. A PPS DSM is necessary for RAS design because reconfigurations affect the entire system and also changes to a system may come from product, process or system or a combination. DSM of products, processes and system is necessary for RAS design because reconfigurations affect the entire system

A reconfiguration scenario was modelled using DSMs in case study one to demonstrate the system scalability and to calculate ROM costs and rates for a TRL2 RAS for a future aircraft wing. Scalable elements representing automation were added to the DSM to calculate costs

and rates to reconfigure for a capacity increase. The new interactions provided information to the designers to document the work involved to reconfigure and calculate the costs and times to reconfigure. A reconfiguration scenario was modelling again in the second case study where the system was reconfigured three times to ramp-up production capacity to 60, 80 and 100 aircraft per month. The DSM was modified each time to represent the reconfigured system. The new interactions were mapped for each reconfiguration used to assess the costs of implementation. Costs and rates were validated by Airbus in PDRs.

This work advances DSM principles to a complete system with product and processes and equipment for RAS design. A complete system view is important because processes are intrinsically related to equipment and product. Al-Zaher (2013) uses DSMs from a tooling hardware perspective only and does not consider process and spatial interactions which carry associated costs and practical constraints which may render a reconfiguration unfeasible. Al-Zaher (*op. cit.*) also only focuses on tooling changes for model change of a specific vehicle, whereas this method focuses on scalability. What's more, this approach is applicable for different reconfigurations such as new technologies or changes to the process because of the system-wide view of interactions, which is not afforded by Al-Zaher's DM.

8.1.5 Limitations of the Design Methodology

Whilst several advantages can be claimed in using the DM, some limitations are inherent which are accounted for here. The DM was developed to satisfy Airbus requirements. These requirements were drawn from an industrial review of Airbus practices and operational needs which could be markedly different in other companies and industries. System design may be more restricted which could limit the use of the DM. It is possible that designers may not be the primary source of design information. In either case, a prescriptive DM would be more appropriate to design a suitable system. However, DSMs could still be used to model reconfigurations. The Airbus derivation of the DM could limit the scope of the methodology to a narrow range of applications. Although, AD and DSMs are design-neutral and can be applied to a wide range of design problems so the methodology could be adapted to suit.

The industrial review found engineers to be the primary source of design knowledge and engineering collaboration as the primary design process. This led to the selection of designer-centric methods. As a result, the DM is fundamentally dependent on designer ability which brings about numerous limitations. The DM relies on design information being captured correctly and completely. Omissions or errors in this information are likely to yield a flawed design where requirements are not satisfied. Correct statement of FRs, DPs and interactions are also dependent on designer ability and could lead to similar penalty if incorrect. However, these are still issues to be contended with at Airbus under current practice where successful design is dependent on designer capability. The gate review and milestone framework is used to check designs for these issues. Designer ability is also a factor in estimating costs and rates. While steps were taken to validate these via Airbus reviews, estimates could still be inaccurate. For most R&T projects at Airbus, experienced-based costing methods are usually appropriate and are the current practice and suitable for R&T needs. Airbus has a costing department which handles complex costing when designs pass TRL4 review. With the design team central to system design, the methodology can be susceptible to bias from certain stakeholders. This facet should also be dealt with under the Airbus gate review framework. A further limitation of the methodology is a required understanding of AD and DSM. While designs can be translated easily into appropriate Airbus formats, designers need to have working knowledge of AD and DSM to exploit benefits of independence and ability to specify scalable and customisable FRs. Successful application of the DM is clearly dependent on designer knowledge, although this is true for current design practice, the DM provides structure and insight because of its basis in AD and DSM which are design methods specifically suited to enhancing the designer during the design process.

Application of the DM is currently a manual process. The time needed to gather design data, carry out design decomposition, construct DSMs and model CAD is in the order of months and years. Such timeframes may not be suitable for other industries. In addition, modelling large numbers of reconfigurations could become labour-intensive as could comparing different systems where reapplication of the methodology could become labour-intensive. The DM lends itself well to software which could semi-automate some aspects of the process which would reduce the design time. Certainly, sufficient time should be allocated to communicate information to all stakeholders and collaboration itself can frequently run over estimated deadlines. Software development is possible but introduces issues for Airbus such as software testing, development costs and training. Software rollout is also subject to security testing and involves some downtime of certain systems.

Other limitations of note are the virtual basis of design which is inevitably subject to physical validation which can be expected of any CAD. The methodology is primarily suited to assembly tooling in fitting with Airbus requirements. The DM could feasibly be adapted to other RMS design problems because of the basis on universal design principles in AD. Note also that successful design of RAS is in part dependent on available technologies to provide the necessary functions for scalability and customisation. The DM has clear limitations and fundamental dependence on designer expertise. It is also potentially limited in scope because of its derivation from unique procedures at Airbus. However, the apparent limitations don't strongly detract from the benefits described when applied in the circumstances presented in the case studies which have been broadly successful for Airbus.

8.2 Aerospace Assembly

The following section explains the significance of the RAS designs in regard to future production and assembly. The DM has been used to create RAS designs for a future NGCW and the current A320 wing which are the first instances of full-scale RAS for aerospace primary structure assembly. Comparison with baselines for current assembly systems evidences reductions in costs and ramp-up time which have implications for reduced backlog and increased revenue. The first case study compares RAS with conventional fixtures for a future aircraft wing and finds ROM CapEx cost reductions of 10% and a ramp-up time reduction of 88% for RAS. However, initial investment in NGCW is 17% higher than A320 baseline. For a 10-year production run, RAS reaches zero backlog in 2028 whereas a conventional approach has a backlog at approximately 1392 and the end of the production run in 2035. The second case study compares a RAS with pulse line assembly for A320 and finds RAS total tooling CapEx to be 41% less than pulse line for a 12-year production cycle. However, initial CapEx is 33% higher for RAS. The RAS design exhibits 50% decrease in ramp-up and 80% reduction in backlog by 2028; validated in an Airbus PDR. The cost savings are comparable to automotive results which are in the range of 30-80% compared to standard assembly lines (Simpson et al. 2006; Simpson et al. 2014). Adopting RAS for production of current and future aircraft increases production capacity and ramp-up rate which results in shorter aircraft lead times. This leads to reduced backlog and increased revenue. For Airbus NGCW, an industrialised RAS improves manufacturing agility where the assembly system can respond to changes in market demand. Greater manufacturing agility would mean capacity could rapidly increase in response to order spikes and prevent accumulation of backlog. Similarly, RAS for A320 production could reduce the current backlog and supply demand for future orders forecast by Airbus.

The designs presented in this thesis are set to be realised as a RAS for Airbus. Designs are to be developed under the R&D technology maturation program within Airbus and used in plans for future aircraft manufacturing strategies. The RAS designs inform future R&D strategy for maturation to production implementation with wider involvement of programs such as factory operations and supply chain logistics. Definition of suppliers and work packages can be based on the build philosophy and designs. In the wider scope, the scalable and customisable architecture means most parts of the system are decoupled. This permits easier introduction of new technologies or processes because of structural independence of the cells and subsystems. This means the system has greater

responsiveness and could likely increase the lifecycle of the factory through updates and retrofitting. The DSMs are well-suited for this process as changes can be mapped as with reconfiguration modelling. DSMs should be used as the design progresses to detail level and for maintaining consistency with functional requirements. Greater traceability is also afforded through the DM structuring of the system architecture.

8.3 Research Limitations

The DM and RAS CAD contribute a significant step to Airbus future production systems. Case study implementations of the DM posit reductions in backlog and increased revenue for costs comparable to conventional assembly which corroborate with results in the automotive sector and internal Airbus studies. The research conducted, case studies and results are not without certain limitations. The extents of these limitations are discussed in this section. Limitations related to the DM itself are discussed in section 8.1.5. Firstly, the case study data is directly sourced from Airbus which includes the reconfiguration scenarios and so the findings are unique to Airbus. The reconfiguration scenarios are based on Airbus requirements and current working knowledge and so are acceptable at present. Alternate scenarios could yield a different system design which exhibits a different response to market change. That said, systems designed with greater independence are more likely to be easier to modify because of the decoupled structure.

In regards to costs, steps were taken to validate the estimations by collaboration with tooling suppliers and separate validation by Airbus. Costs can be relied upon only to the extent that the estimations are reasonable. Certainly, cost analysis should be ongoing and integral to the RAS maturation at Airbus. Costs were also limited to tooling CapEx only as defined in section 7.6.4. This is standard practice at Airbus for this type of project but the wider impact of RAS costs for Airbus should be considered in future developments. Under the Airbus TRL methodology, ROM benefits are stipulated at TRL2 and ROM costs are not required for pass and proceed until TRL4. The second case study provides detailed CapEx costs for comparison with a baseline in support of the DM validation. Airbus PDR found costs to be reasonable. However, R&T focus is usually on technical development rather than cost, true costs are only apparent prior to full-scale implementation.

The case study results put forward figures for ramp-up reduction in comparison to current assembly. Ramp-up time is made up of estimates for design time, process time and implementation time. Current practice is for tooling suppliers to estimate these values based on experience. These values were later verified by Airbus stakeholders in TRL reviews and PDRs and found to be reasonable. For case study two, the A320 RAS uses the same processes based on SOIs and the build network but employs different tooling methods and additional equipment to increase simultaneous work. The inclusion of the processes in the design was brought about by using the Customer Attributes Gathering and Customer Needs to form Constraints limiting the design to current processes. This goes a substantial way to establish the time-related estimates as reasonable to validate the DM. But, work is ultimately subject to testing which will occur under the Airbus TRL process to ensure systems are viable, as with any new assembly system.

The 3D designs must also be considered with the following limitations. For all applications of the DM, dependence on designer expertise is true for all the design work. However, this is currently the case at Airbus with an ad-hoc approach to ASD. The design process is enhanced by application of the methodology by systematic decomposition to guide the designer from abstraction to detail design with consistency with Customer Needs. The use of AD and DSM are used in this manner to support the designer by systematisation and visualisation. The design was carried out to a level of detail sufficient for demonstrating the working principles of the cells and for preparation of build philosophies. Design has progressed to detail level in some cases to further substantiate the designs. In most cases, extra design effort is necessary to progress to detail level of design. Provision for this in the methodology is afforded by AD which progresses from high-level abstractions to detail design including feature dimensions and tolerances. In addition, extra design work is required for auxiliaries such as wiring, cable routing, airlines, vacuums and hydraulics. It is generally common practice to add these in later stages of design. Successful

implementation falls to appropriate consideration from designer experience in the 3D mapping phase. Though this is not ideal, it is current practice at Airbus and routing issues generally do not result in redundant design.

8.4 Research Questions

Research questions were stated in Section 1.9 to guide the research. This section offers consideration the extent to which the research has answered these questions. Questions are dealt with in numerical order with the overall research question considered last. Question one concerned the formulation of assembly system requirements taking into account system requirements as well as existing knowledge to design systems that make best use of industrial knowhow. A process of gathering and organising design data was specified as part of the DM outlined in Chapter 5 which was then demonstrated for future and current aircraft assembly systems in Chapter 6 and Chapter 7 respectively. The DM created RAS designs from a set of Customer Needs and Constraints which combined lessons learnt, current R&D and proven processes and tooling to guide design and define the boundaries of acceptable solutions. Question two centred on specifying scalability and customisation from the design outset, as dictated by Koren (*op. cit.*). Design rationale was presented as part of the DM. Scalability and Customisation requirements can be drawn from Customer Needs for product family and volume and then specified in a system design using AD theory. These needs are mapped to FRs of a system which specifies the range of production rates and model changes. Specification of physical DPs to satisfy the FRs thereby embodies the characteristics necessary for a RAS. This was demonstrated in both case studies where the RAS were designed then reconfigured. The third question led a line of inquiry to go beyond a system architecture to practical designs for Airbus industry. The DPs specified using AD went some way to provide the design intent but lacked any strategy for physical implementation other than ad-hoc designer effort. DSMs were introduced as part of the methodology to integrate the DPs into practical physical systems in 3D CAD. The DSMs were then used to model reconfigurations in regard to question four. Question five was stated regarding the comparison of a RAS and conventional assembly system for investment. Airbus targets to improve assembly provided basis for the research aims. RAS were shown to have notable benefits to ramp-up, production capacity and cost compared to the current baseline. Though, analysis was limited to production scenarios particular to Airbus' immediate interests and the current market.

In following research questions one through five, the main research question has been satisfied by a formal DM validated by two Airbus case studies. The methodology has been applied for a future aircraft wing and a current aircraft wing which have both yielded RAS for cost-effective wing structure assembly. The RAS for NGCW passed Airbus PDR and TRL2 review and will progress with ongoing development with the NGCW program. The RAS for A320 high-rate production has passed Airbus PDRs and proposes a new strategy to address the current backlog. Both RAS designs require development from manufacturing and the wider Airbus consortium but form a significant step towards future wing assembly.

8.5 Summary

Chapter 8 presents discussion of the DM and its significance to the fields of RAS design and aerospace assembly. Evidence in case studies has shown that using the DM, assembly systems can be designed to be scalable and customisable from the outset and embody the characteristics of reconfigurability when designed accordingly. The main features of the methodology which provide this capability are described with noted limitations to dependence on designer expertise. Case study results indicate that the RAS designed using the methodology have improved capabilities for ramp-up time, production capacity and cost, albeit with limitations to the scenarios presented. Impact of the RAS designs to Airbus is discussed which points to inclusion in future development programs, albeit with support and congruity of the wider Airbus consortium. Limitations of the research are discussed including details highlighting the estimates for costs and times which were validated by Airbus. Discussion closes with critique of the investigation in regard to the research questions.

Chapter 9 Conclusion

A full investigation into Reconfigurable Assembly System (RAS) design has been carried out on behalf of Airbus, bringing together academic and industrial discourse. A novel RAS design methodology has been presented to address design complexity and the specific needs of aerospace manufacturing. The RAS designs are made possible by using customer needs and existing knowledge to systematically specify scalable and customisable functionalities from the outset. The design methodology is applied in two case studies for wing assembly to produce factory designs which are compared with current Airbus baselines. The RAS demonstrate capability to change in structure for rapid increase in capacity at comparable cost to fixed systems. Greater capacity and shortened ramp-up time evidently reduces backlog compared to current systems. The first case study focused on technical development of a RAS and found potential ramp-up reduction of 88% and 10% less Capital Expenditure (CapEx) over 10 years. The second case study for a current wing found reductions of 50% to ramp-up and 41% less tooling CapEx compared to a pulse line for a 12-year production cycle. This chapter brings the research to a close and sets an agenda for future work. The project aim is restated and conclusions are drawn from the research followed by a summary of the contributions to knowledge. Lastly, possibilities for future work are explored for continuing the research.

9.1 Research Aim

This research set out to design RAS for wing structure assembly with the aim of increasing productivity in response to forecasted increase in global air travel demand and lower production costs of developing competitors. Airbus targets are:

- 30% reduction in capital expenditure on tooling
- 50% increase in production capacity
- 50% or more reduction in ramp-up time
- 40% reduction in overall costs

This is to be achieved incrementally by 2050. Airbus forecasts production of over 22,000 single-aisle aircraft by 2033, inclusive of current backlog of over 6000. Airbus is preparing to meet this demand by increasing supply of the current aircraft and developing new aircraft with improved ramp-up and production rate. The focus for the project has been the primary wing structures which are assembled by Airbus UK in Broughton, Wales. The current wing assembly systems are slow to respond to increases in demand where increasing production rate by building additional fixtures takes approximately 24 months. RAS are designed from the outset for rapid increase in capacity and function and thus offer significant advantages for wing assembly at Airbus. The aim was to design RAS for cost-effective wing structure assembly to understand the benefits and implications. A suitable Design Methodology (DM) was needed to manage the design complexity. A literature review found gaps in current RAS design methodologies (RASDM), which were more suited to variety and customisation in the automotive industry. A new methodology was needed to implement RAS suitable for Airbus. Research questions presented in Section 1.9 were followed to develop the research and restated here:

1. *How can existing knowledge and product requirements be translated into assembly system requirements?*
2. *How can scalability and customisation be specified from the design outset?*
3. *How can RAS requirements be translated into working assembly system designs?*
4. *What methods can be used to model reconfigurable implementations?*
5. *How does an Airbus RAS compare with a conventional assembly system for investment?*

Each question was researched in turn and considered retrospectively as the DM was developed. Using the research questions to search literature, existing research, applicable tools and principles were collected and compared with industrial requirements. The collection of research which satisfied requirements was ordered to form a theoretical DM. The research was developed further into a formal DM for functional testing. The following section details the development of the DM.

9.2 Development of a RAS Design Methodology

A review of Airbus industrial practices was conducted to specify the requirements of a DM. A literature review followed and found design methodologies only partially satisfied the DM requirements. Most complete RAS design methodologies focused on customisation in automotive examples. Little research was available on design for capacity increase through the RAS characteristic of scalability. Furthermore, no evidence of RAS or RASDMs were found for aerospace applications. Further still, the existing RAS design methodologies seldom mentioned application in an industrial context where design is a multi-disciplined collaboration with ongoing and iterative development. A new methodology was developed for Airbus to design RAS for improved capacity and ramp-up capabilities.

Using the DM, key design data including existing knowledge, R&D and lessons learnt now become explicit components of the assembly system requirements, which the designer combines with requirements for production rate and variants. The Customer Needs for reconfigurability are thereby inherent and form the basis for systematic design decomposition. This set of requirements is decomposed into sub-functions for scalability and customisation consistent with Customer Needs. The principles of Axiomatic Design (AD) govern the design decomposition and ensuring consistency with the primary requirements. The functional architecture for a RAS is then embodied in physical designs by translating the design decomposition into Design Structure Matrices (DSM). The interactions apparent between the DSM elements guide 3D design and practical integration and also modelling reconfigurations. Thus, scalability and customisation is specified at the design outset, congruent to the actual wing assembly development and a RAS is realised in virtual space.

The DM overcomes the limitations of existing design methodologies which focus on variety rather than capacity and ramp-up. What's more, the implementation of two aerospace case studies as part of actual Airbus projects has shown RAS design advance into the field of wing assembly for the first time. The DM has been used to produce reconfigurable designs for future and current aircraft wings at Airbus. Although, development work is still needed to progress the RAS designs to production maturity. And, some limitations to the DM are apparent despite the advances. The DM is current limited to a manual process which is time-consuming and the success of the methodology is fundamentally dependent on designer experience so is still dependent on rigorous Airbus design reviews.

9.3 RAS Designs for Cost-effective Aerostructure Assembly

Extensive CATIA and DELMIA design work was carried out by the author to produce the RAS designs presented in the two case studies. The author acted as designer of the system architecture using the DM and technical authority during the design of NGCW under Airbus procedure. 3D CAD was carried out by the author and suppliers. Final design was subject to Airbus internal review with senior engineers. The author was sole designer of A320 RAS and produced the system architecture using the DM and all designs and 3D CAD.

The DM has been used to design cost-effective RAS for aerostructure assembly. Two RAS are presented, one for an in-service aircraft wing and one for a future aircraft wing in development. These future assembly systems have designed-in capability to reconfigure to market demand; achieved through application of the DM which was formulated specifically to complement Airbus design practices. The 3D virtual designs developed in the case studies are the first instances of full-scale RAS for wing structure assembly. Until

now, wing assembly has been carried out in dedicated fixtures or production lines with no capability for capacity increase other than time-consuming fixture duplication which delays aircraft delivery. RAS are used in automotive assembly but focus on variety rather than ramp-up. Existing technologies used for assembling in-production aircraft are available to provide the accuracy and mobility for reconfigurable assembly. Despite this, they have not been integrated in such a way to provide functions for scalability. The DM allows the designer to incorporate these technologies in the design process to create a changeable structure for increase in rate. The RAS developed in the case studies demonstrate ramp-up and capacity increase capabilities by modelling the changes using DSM and evaluating for new production rates and cost in conjunction with a tooling supplier. The first case study focuses on technical development of a RAS and found:

- Ramp-up reduction of 88%
- 10% less CapEx over 10 years

Albeit at a speculative rough-order-of-magnitude. The second case study for a current wing found reductions of:

- 50% to ramp-up
- 41% less tooling CapEx, compared to a pulse line for a 12-year production cycle

Time and cost estimates are subject to limitations of experience-based costing methods but were corroborated in Airbus design reviews which also validated the design feasibility. The RAS designs set a precedent for the future of aerostructure assembly, which has been made possible by designing from the outset using a novel DM suited to Airbus. Case study application of the DM followed by evaluation of 3D designs indicate RAS are a viable means to reduce ramp-up time and long term costs of wing assembly. The designs will undergo continued development at Airbus as part of wider aircraft programs and are set for use in future production.

9.4 Contributions to Knowledge

Several contributions to knowledge can be claimed from the presented research, which address specific shortcomings drawn from reviews of academic journals. Rationale supporting the contributions is presented throughout the thesis as is dictated by the investigation. A summary of these contributions is presented in this section. Searches for a DM to develop a RAS in accordance with Airbus design practices found existing methodologies lacking certain features but could potentially be adapted to suit Airbus needs. These deficiencies led to the innovation of a new DM, which is a combination of methods adapted to suit Airbus ASD criteria. Aside from being an end-to-end DM, four novel aspects were introduced to make RAS design suitable for aerostructures assembly:

- RAS Requirements Framework
- Application of AD to RAS to specify Scalability and Customisation functionality
- Application of DSMs to create a PPS architecture model with interactions pertinent to RAS design
- Application of PPS model for modelling reconfigurations and implementation

9.4.1 RAS Requirements Framework

Firstly, a RAS Requirements Framework was developed to produce a set of system requirements which could account for influential data from R&D and current production, as well as tacit knowledge and experience. Existing design methodologies forgo this provision despite these sources of data having fundamental impact on the system design.

9.4.2 Application of AD to RAS Design

The second contribution is the application of AD to specify exactly the right levels of scalability and customisation functionality for a changeable system which can restructure to change in demand. The requirements produced using the framework are decomposed into sub-functions which are a mixture of flexible and non-flexible modules which make up the system architecture. Hierarchical decomposition of the requirements in this manner enables scalability to be specified where it is needed to satisfy higher-level requirements for capacity increase. The sub-functions correspond to a physical system architecture which is later integrated. This ability was absent from existing RAS design methodologies, which focussed on customisation for product variety.

9.4.3 Application of PPS DSM to RAS design

On satisfactory completion of the system architecture a method was created to integrate the physical system, constituting contribution three. The DPs of the system architecture are translated into a DSM (System) along with separate DSMs for the wing (Product) and the assembly operations (Process). Interactions are mapped for each DSM as well as the interactions between domains and were specifically formulated for reconfigurable system design. These interactions govern the constraints of 3D design and, provided the designer maintains consistency with the DSM structures and interactions will create a RAS in virtual space satisfactory to the original requirements established in the RAS Requirements Framework. Note, the compatibility of AD and DSM is well documented but previously offered no insight into applications for RAS design when considering it is a changeable system. Previous work focused on one domain only whereas with a reconfigurable system changes can impact multiple domains.

9.4.4 Reconfiguration Modelling

The PPS model of the RAS provides complementary usage for reconfiguration modelling, which is the final contribution. Prior work focused only on using DSM in one domain to model changes for model variants and made no distinction on the type of interaction. The PPS DSM aspect states mechanical, spatial and process interactions across the entire system which gives greater insight into costs and time to reconfigure as well as opening up possibilities to test more scenarios such as model change.

9.4.5 Summary

The contributions in combination with general engineering rationale provide the means to develop RAS which are cost-effective and suitable for wing assembly. This advancement expands the field of RAS design and broadens the possibilities for applications of reconfigurable assembly at industrial level now that such a methodology exists.

9.5 Future work

The research presents a new DM which has been used to systematically develop two RAS for wing structure assembly. The system designs set a precedent for the future of aerostructure assembly and the DM itself opens up new possibilities for future research. Future work should revolve around advancing the RAS to production capability of in-service aircraft. For the current wing this will mean progression through the Airbus Technology Readiness Level (TRL) maturation process including relevant supplementary work. For the future aircraft wing, the RAS should continue development in tandem with the aircraft development program as well as the R&D TRL program. Future endeavours regarding the DM should continue to refine the methodology for usability and testing its use in further case studies; with respect to the broader RAS research.

9.5.1 Additional Case Studies & Future Applications

For the DM, continued work can address some of the limitations found through the course of the research as well as use for further innovation in RAS research. The methodology has

been developed for issues particular to Airbus; however many of these issues are shared in other industries. The methodology could be applied to other aerostructures and indeed other industries for further validation. The methodology is specifically suited to complex structures with long lifecycles where ramp-up is a prominent challenge. Typical applications could include military vehicles (land, sea or air) or low-to-medium volume automobiles.

9.5.2 Software Development

Development into software would further enhance the methodology by reducing the design time and could be used with PLM software for reconfigurations over the system lifecycle. Greater automation of the manual processes of mapping DSM interactions would shorten the design time. This would allow more time to be spent testing different reconfiguration scenarios. Integration with CAD modelling could also greatly shorten design time by eliminating the need for remodelling. Future design work could then model multiple RAS which could be compared for a greater number of scenarios. This would provide a richer view of potential systems to better inform investment analysis. The methodology could be modified to include one of the existing reconfigurability indexes calculated as a function of DSM interactions (i.e. independence) for comparing different systems.

9.5.3 Airbus RAS Maturation

The case studies present the first instances of production-scale RAS for aerostructures and much of aerospace RAS is still in its infancy. A great deal of work is necessary to bring RAS capable of assembling in-service aircraft. Industrial progression of RAS is a significant change in procedure for Airbus which has far-reaching ramifications. Many of the procedures in place revolve around the current practice and so multiple departments will have to adopt new practices. While this is a large undertaking, the lifecycles of aircraft production do permit such changes and restructuring has taken place in recent times to address current backlog. The expected procedure is to begin with consideration of the implications of the designs in the broader scope for Airbus. Followed by, structuring the development into work packages which are sub-managed by the relevant stakeholders and suppliers. A chief implication centres around acquiring certification for the new systems. The RAS for current aircraft uses many existing processes so certification should be straightforward. Certification of the future system is a much larger undertaking, where the wing design is in early stages and so will be certified as a new system. The cost implications are equally important with both the RAS. The future RAS bears more unknowns given the ongoing technical development of the wing which is not yet at design freeze. For the current aircraft, costs are more precise but still require deeper investigation through Airbus costing departments with consideration of supplier negotiations and government subsidisation. In both cases, next phases should consider other necessary production costs in regard to factory operations. Equally, areas for cost reduction are feasible depending on make vs. buy analysis. Also, costs of metrology and mobile robotics may decrease with Airbus negotiation and risk-sharing partnerships. Logistics is also a primary area for investigation considering the increase in production capacity. Airbus supply chains must be able to cope with issues relating to increased demand. Beyond the systems presented, RAS have potential in other areas of aerostructure assembly. Fuselage variants are feasible for reconfigurable assembly.

9.5.4 Standardisation

Future investigations could even consider how RAS can be applied to cross-model production for future generations of single-aisle and twin-aisle aircraft, given sufficient technical development. Ultimately, this could result in modular aerostructures as seen in recent automobiles. Introducing greater standardisation in this manner lends to commonality in assembly tooling, as shown by automotive manufacturing gains in productivity. Ramp-down should factor into future considerations where a system has

reached the end of the production lifecycle. Greater standardisation could see systems reused and deployed elsewhere, which would enable efficient ramp-down.

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Appendix A: C.A.M Tooling Supplier Benchmark

CAM Benchmark

The Centre for Aerospace Manufacturing (C.A.M) provided cost estimations validation as a formal quotation from a detailed design review of the RAS and Baseline. The design review was also conducted with expert stakeholders at Airbus UK to independently verify technical feasibility, rates and costs. A benchmarking exercise was carried out to outline the cost estimating capabilities of C.A.M.

The C.A.M provides assembly tooling and automation solutions to the aerospace industry. Projects range from low-TRL innovations and testing to high-TRL production systems. As well as technical expertise, C.A.M also have costing expertise. Often conduct reviews of existing systems and come up with innovations and a supporting business case. Tooling and assembly systems require a business case to justify implementation and so most projects include a business case detailing estimated capital expenditure and payback period.

Company Portfolio

- Assembly Tooling Hub for Airbus UK between 2009 – 2015
- Business and engineering expertise recognised by MBA, PhD and senior roles in industry
- Previous project cost sizes - £100k - €5 million
- Project Duration – 3 months up to 5 years
- PRINCE2 Project Management
- ISO:9001 Accredited
- Customers – Airbus UK, Airbus Helicopters, GKN, BAE Systems, GE, MTC, NCC
- Suppliers – ElectroImpact, Hyde, AeroTech, NIS, ABB, Kuka, De-Sta-Co, AMF, THK, Festo

Technical Expertise

- Aircraft assembly tooling design and manufacture
- Cost modelling expertise in aerospace tooling design and manufacturing
- Assembly process planning for aircraft structures
- assembly tooling manufacturing, build and assembly
- Manufacturing technology maturation and insertion (industrialisation)
- Novel tooling and assembly concepts
- composite component tooling design and manufacture
- aircraft component design and requirements
- Assembly system metrology
- CATIA / DELMIA digital designs, simulation and manufacturing environment
- Aircraft tooling and assembly programme management

Previous and Current Projects

- Lean improvement and novel tooling technology insertion for civil aircraft primary structure assembly. 6 month project with a 12-week Value Stream Mapping exercise of the assembly line. Assembly system was reviewed for continuous improvement projects to improve production rate and quality. A range of tooling innovations were conceived and supported with time studies and technical feasibility. Business cases were prepared for selection by the customer along with TRL.
- Future factory designs for high-rate tooling and assembly for wing structures. One year project delivered TRL2 documentation, 3D CAD and tooling and assembly simulations. future factory layout for tooling and assembly. State-of-the-art review carried out for wing structure assembly. Current processes were reviewed as baseline. Existing R&D was reviewed and incorporated into designs. Simulated process plan with times and ROM costs for tooling, novel technologies and options decision-making
- High rate tooling and automation solutions for primary structure assembly. 3 month project to review current assembly line processes and replace manual methods with automated solutions to increase production rate. Business case with estimated cycle times and costs with payback period.
- Flexible assembly cell with collaborative robots for multiple aerostructure subassemblies.
- Integrated metrology and vision system for aerostructure subassemblies. Technology maturation and industrialisation which will be retrofitted into current assembly line.
- High-volume wing assembly technologies demonstrators (TRL3 & 4). Two year R&D project testing and developing new tooling and assembly techniques for high rate production.
- Robotic fastening cell feasibility study. 3 month investigation into implementing robotic fastening to replace the current manual fastening process. Systems costs and business case provided showing investment and savings.

Costing Process

The costing process is an experience-based approach based on detailed review of the requirements and design followed by a cost-breakdown of the system components. The costing experience of members ranges from 5 to 30 years. Cost estimation accuracies are +/-10% based on historical estimates versus the actual cost. The costing process begins with discussions on customer needs and requirements elicitation which are then agreed. A design process follows which adds detail which can be costed against. The design process used is dependent on the project needs and generally includes a build philosophy and storyboard depicting the working principles and estimate capabilities. 2D or 3D schemes are used. Once a suitable level of detail is reached, costs are estimated and broken down into design, manufacturing, capital equipment and integration costs. A BOM is produced.

Appendix B: Airbus PDR Meeting Minutes


AN EADS COMPANY

MINUTES
TO
COPY
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FROM AbdulRahman El-Nounu
Subject RAS Design Review
DATE 10.03.2016

SUBJECT OF MEETING
Reconfigurable Assembly System – Design Review

DATE OF MEETING
10.03.2016

PARTICIPANTS
AbdulRahman El-Nounu [AR] Airbus
Tom Jefferson [TJ] Airbus/UON

Location
WebEx

PART TIME ATTENDANCE

OBJECTIVE
Design Review of A320 Primary Structures Reconfigurable Assembly System

- design feasibility
- validate cost and rate estimations
- Risks

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AGENDA

- Present reconfigurable assembly system and baseline
- Discuss feasibility and implications of reconfigurable tooling and automation designs for wing assembly
- Validate cycle times
- Appraisal of costs
- Highlight potential risks and unknowns

MINUTES

1. Introduction
 - a. **Discussion:** TJ presents overview of research, background of RAS, production data, assumptions and aims of the design review.
 - b. **Discussion:** TJ gives overview of RAS for A320 designed for rates of 40 up to 100 per month
 - c. **Outcome:** AR happy with overview and believes assumptions are reasonable
2. Cell 1: Spar Loading
 - a. **Discussion:** TJ presents cell 1 automation and tooling designs and explains processes. Ramp-up approach is explained. Costs and cycle times are also presented for rates 40, 60, 80, 100.
 - b. **Outcome:** AR satisfied with spar loading process and tooling designs. Rates believed reasonable which are similar to current process times. Costs are reasonable for design and equipment.
3. Cell 2: Rib Assembly
 - a. **Discussion:** TJ presents cell 2 tooling concepts and explains working principle for rib loading and assembly. AR queries positioning of ribs to spars. TJ explains the method will be same as the current manual method using step gauges. TJ shows detailed designs of strongbacks.
 - b. **Outcome:** AR satisfied with rib assembly process and tooling designs. Cycles times and costs reasonable. AR satisfied with ramp-up process.
4. Cell 3: Locate Skins
 - a. **Discussion:** TJ presents cell 3 tooling concepts for skin location. AR queries skin location method which is different to the current process i.e. no tooling for location. TJ explains is used extensively in automotive industry and is adjustable using shims and is repeatable once set up. AR happy with explanation. AR mentions cycle times are very similar to current process. AR queries vacuum cups on skin lifting frames. TJ states that pneumatic safety clamps are used in addition to vacuum cups.
 - b. **Outcome:** AR satisfied with designs and ramp-up. Cycle times and costs reasonable.
5. Cell 4: Skin Drilling
 - a. **Discussion:** TJ presents cell 4 design which utilises mobile robotic platforms for skin drilling. Applications of the technology on other aerospace structures discussed. Accuracies discussed. AR queries ramp-up process of adding mobile robotics. Questions that adding a robot necessitates modification to the process of the first robot. TJ cites design time factored into the costing to account for this change.

- b. **Outcome:** AR satisfied with design and reconfiguration. Satisfied that costs a reasonable and cover extra design time.
- 6. Cell 5: De-burr Wingbox
 - a. **Discussion:** TJ presents deburr cell for deburring and cleaning wing after drilling. TJ highlights deburr stations which are mobile and used to transfer wing skins to fastening cells. AR explains it is critical that stations are mobile. TJ shows cycle times and costs. TJ highlights location method is same as MAF. TJ highlights pneumatic clamps are used to hold skin during deburr.
 - b. **Outcome:** AR satisfied with design of deburr cell and finds costs and cycle times reasonable.
- 7. Cell 6: Lower Cover Fastening
 - a. **Discussion:** TJ presents LC fastening cell design. Highlights process is identical to current process and ramp-up is achieved by adding operators.
 - b. **Outcome:** AR sees no faults with design because it is similar to current practise and adding labour is achievable. Costs and cycle times appear reasonable.
- 8. Cell 7: Upper Cover Fastening
 - a. **Discussion:** TJ presents UC fastening cell design. Highlights process is identical to current process and ramp-up is achieved by adding operators. Highlights similarity to LC fastening.
 - b. **Outcome:** AR reiterates similarity to current practise which is very low risk. Costs and cycle times appear reasonable.
- 9. Baseline and comparison with RAS
 - a. **Discussion:** TJ presents the baseline factory which will be compared with the RAS for CapEx, Backlog and Capacity. Assumptions are highlighted. Costs and rates are presented. Ramp-up method is Airbus' current practice. AR confirms.
 - b. **Discussion:** Graphical data of cost, capacity and ramp up time are compared for the baseline and RAS designs. AR highlights Airbus interest in faster ramp up and tooling flexibility. Mentions general agreement at Airbus that RAS has faster ramp up but requires higher initial investment. RAS is justifiable given the current backlog, forecasted orders and single-aisle replacement aircraft.
 - c. **Outcome:** Logical and fair comparison of two assembly systems with different approaches to ramp up of production showing RAS has faster ramp-up which has been designed from the outset.

MINUTES

TO
COPY
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FROM **Mike Redman**
Subject **RAS Design Review**
DATE **24.03.2016**

SUBJECT OF MEETING

Reconfigurable Assembly System – Design Review

DATE OF MEETING
24.03.2016

PARTICIPANTS

Mike Redman [AR]	Airbus
Dave Tomlinson [DT]	Airbus
Tom Jefferson [TJ]	Airbus/UoN

Location
WebEx – Think Tank Room
71

PART TIME ATTENDANCE**OBJECTIVE**

- Design Review of A320 Primary Structures Reconfigurable Assembly System
- design feasibility
 - validate cost and rate estimations
 - Risks

AGENDA

- Present reconfigurable assembly system and baseline
- Discuss feasibility and implications of reconfigurable tooling and automation designs for wing assembly
- Validate cycle times
- Appraisal of costs
- Highlight potential risks and unknowns

MINUTES

1. Airbus reviewer background
 - a. **Discussion:** TJ requests roles and experience of DT and MR.
 - b. **Outcome:** MR Background - maintenance and fitter in automotive manufacturing for 14 years. Manufacturing engineering background and detailed knowledge of automation. Joined Airbus in 2003 as automation specialist until 2011. Airbus UK work-stream leader in Manufacturing Engineering R&T specialising in automation.
 - c. **Outcome:** DT Background – 30 years aircraft tooling at Airbus Filton. Tooling lead for Airbus UK since 2011.
2. Project Introduction
 - a. **Discussion:** TJ presents overview of project and background information. Project based on historical data. Explain premise of reconfigurable assembly system has faster ramp up because system is designed to increase in capacity. Main metrics are explained with examples. TJ shows predicted orders scenario.
 - b. **Outcome:** MR and DT happy with overview and design review can begin cell by cell.
3. Cell 1: Spar Loading
 - a. **Discussion:** TJ presents cell 1 automation and tooling designs and explains processes.
 - b. **Discussion:** DT points out Airbus are trying to move away from cranes because they end up being used for multiple tasks and so processes needing cranes are left waiting. Known as 'jig-lock'. TJ states each crane is dedicated and should only have translation in one direction. TJ and DT agree this isn't always possible.
 - c. **Discussion:** TJ explains spar loading process. DT highlights spars have quite a lot of compliance and so loading fixture may need some adjustment capability. Also possible to use a rigid loader given further investigation.
 - d. **Discussion:** TJ presents rates and costs and cost breakdown. MR questions sources for production times. TJ points out times are sourced from current cycle times. MR suggests including sources when presenting to production team.
 - e. **Discussion:** MR & DT critique LE and TE delivery to line. One option is to deliver in a frame to speed up loading even further. This can be noted as a condition of supply.
 - f. **Outcome:** MR & DT happy with Cell 1 and believe to be reasonable.
4. Cell 2: Rib Assembly
 - a. **Discussion:** TJ presents cell 2 tooling concepts and explains working principle for rib loading and assembly. Rates and costs also presented.
 - b. **Discussion:** MR & DT satisfied with design but question if it is possible to load all ribs together for minimum cycle time. TJ explains some of the smaller ribs index together but are not shown in the presentation but are in CAD format.
 - c. **Discussion:** MR & DT question cycle time at rate 100. Could be a potential risk. TJ explains a lot of labour content but is achievable because is over a longer period of time which is factored into the ramp-up time.

- d. **Outcome:** MR & DT AR satisfied with rib assembly process and tooling designs. Cycles times and costs reasonable.
5. Cell 3: Locate Skins
 - a. **Discussion:** TJ presents cell 3 tooling concepts for skin location as well as cycle times and rates. MR & DT query cycle times. TJ quotes current skin loading on A320 which is about 30 mins so high rates are possible in a dedicated cell. Cost of the cell is increased because of requirements for two cranes and two lifting frames.
 - b. **Outcome:** MR and DT satisfied with designs and ramp-up. Cycle times and costs reasonable.
6. Cell 4: Skin Drilling
 - a. **Discussion:** TJ presents cell 4 design which utilises mobile robotic platforms for skin drilling. Applications of the technology on other aerospace structures discussed. Accuracies discussed. MR would like to see detailed takt time breakdown. STeP currently drilling both skins simultaneously. TJ explains dedicated cell has been designed with cycle times in mind so can utilise one robot as opposed to two to reduce costs. TJ explains cells are all equally balanced. MR suggests summing up the processes in each cell to show they are balanced.
 - b. **Outcome:** MR & DT satisfied with design and reconfiguration. Satisfied that costs are reasonable and cover extra design time.
7. Cell 5: De-burr Wingbox
 - a. **Discussion:** TJ presents deburr cell for deburring and cleaning wing after drilling. TJ highlights deburr stations which are mobile and used to transfer wing skins to fastening cells. TJ highlights location method is same as MAF. TJ highlights pneumatic clamps are used to hold skin during deburr. DT asks for clarification on skin clamping for safety. TJ explains skins are fastened in cells 6 and 7. TJ shows cycle times and costs with breakdown.
 - b. **Outcome:** MR & DT satisfied with clarification of safety and cost and rate estimates.
8. Cell 6: Lower Cover Fastening
 - a. **Discussion:** TJ explains skin arrives on frames from cell 5 and are lifted into position using cranes. MR & DT discuss holding the form of the panel and repeatable loading onto the wing box. TJ shows how this is possible with the tooling location design and frame holds skin form. MR suggests stating the repeatable panel loading procedure in the presentation in future. DT states covers are very strong and so require reinforced frames which may be too heavy. Will require FEA study to understand deflection.
 - b. **Outcome:** MR & DT happy with concept but future work will require investigation. Alternative would be to use the current method of skin relocation which should be possible for cycle times because of the dedicated cell. MR & DT happy with costs.
9. Cell 7: Upper Cover Fastening
 - a. **Discussion:** TJ explains Upper cover fastening is reverse of LC fastening and so has similar processing times and costs.
 - b. **Outcome:** MR & DT happy design and figures are reasonable.
10. Baseline and comparison with RAS
 - a. **Discussion:** TJ explains baseline and costs breakdown. TJ reiterates orders and backlog. Graphical comparisons are shown for rates. TJ shows reconfigurable line has higher rates and faster ramp up than baseline of duplicating lines. TJ shows CapEx figures and highlights differences. TJ explains design principles and how RAS are designed from the outset. TJ explains benefits of reconfigurable assembly system is capacity is easily added because of prior design effort for scalability and customisation. MR asks for clarification on reconfigurable elements. TJ explains reconfiguration is by adding automation and labour in predesignated places. DT suggests reconfigurable line. MR & DT would like changes to

presentation and more slides before cell descriptions. DT would like to see more reconfigurable tooling in the future.

- b. **Outcome:** Costs and rates are believed to be reasonable and comparable to current projects. Designs are technically feasible and share much of the current processes. Reconfigurable principles applied to line allow greater ramp-up compared to baseline.