

Reconfigurable Assembly System Design Methodology: A Wing Assembly Case Study

Thomas G. Jefferson, Panorios Benardos, and Svetan Ratchev
University of Nottingham

ABSTRACT

Current assembly systems that deal with large, complex structures present a number of challenges with regard to improving operational performance. Specifically, aerospace assembly systems comprise a vast array of interrelated elements interacting in a myriad of ways, resulting in a deeply complex process that requires a multi-disciplined team of engineers. The current approach to ramp-up production rate involves building additional main assembly fixtures which require large investment and lead times up to 24 months. Within Airbus Operations Ltd there is a requirement to improve the capacity and flexibility of assembly systems, thereby reducing non-recurring costs and time-to-market.

Recent trends to improve manufacturing agility advocate Reconfigurable Assembly Systems (RAS) as a viable solution. Yet, adding reconfigurability to assembly systems further increases both the operational and design complexity. Despite the increase in complexity for reconfigurable assembly, few formal methodologies or frameworks exist specifically to support the design of RAS.

In this paper, a novel RAS design methodology is specified to address the design complexity. The methodology is a holistic, hierarchical approach to system design which integrates reconfigurability principles, Axiomatic Design and Design Structure Matrices. A wing assembly case study is used to illustrate how the methodology translates reconfigurability requirements into a system that is scalable and flexible from the outset. The resultant reconfigurable cell design assembles the wing's spars and ribs with ramp-up capability from 40 to 100 aircraft per month. Cell designs are presented as CATIA models. The data used is CAD data from a current single aisle wing. Production data is sourced from current single aisle assembly.

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INTRODUCTION

Future aircraft production faces increasingly turbulent changes in market demand and model configurations driven by new global competition and airline operator requirements. To remain competitive, aircraft manufacturers must reduce time-to-market on new aircraft variants and shorten lead time to reduce backlog on current orders. This has an impact on manufacturing where supply cannot meet demand.

Current assembly systems aren't designed to produce multiple wing variants and so model variants require extensive changes or new fixtures which delays time-to-market.

Reconfigurable Assembly Systems (RAS) are proposed as a cost-effective solution. RAS are designed from the outset to rapidly change in structure to meet new customer demands. Despite enabling technologies, system designs are not augmented for rapid change in structure for ramp-up or model change. A system which reconfigures calls for additional design contribution to apportion scalable and customisable functions. Few methodologies exist to address the additional complexity and lack applicability in real-world contexts.

The paper presents a novel RAS design methodology which combines design methods to develop assembly systems which permit cost-effective ramp-up. The methodology integrates design methods to translate requirements and existing knowledge into physical designs. Systems can be designed from the outset for specific reconfigurable functionality to maximise utilisation and minimise cost. The design methodology is applied to a wing assembly case study to show how a RAS could be designed to have ramp-up and model change capabilities.

BACKGROUND

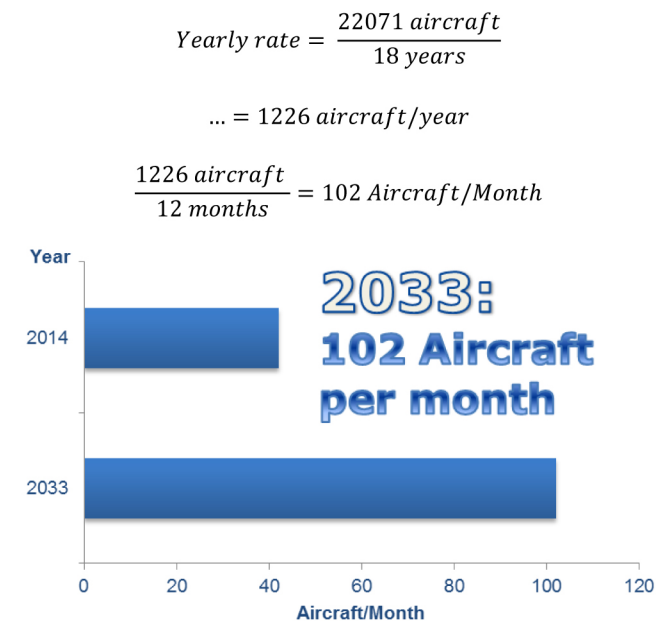
Aerospace Assembly Systems

Aerospace assembly systems join components and sub-assemblies to build the primary aerostructures which include the wingbox, fuselage, empennage and landing gear. Wing assembly systems consist of monolithic assembly fixtures designed specifically for one wing type. The fixtures are not designed to be modified for changes in the aircraft geometry or production rate increase [1]. Increasing production rate involves commissioning duplicate fixtures where lead time alone is up to 24 months [2]. For aerospace companies, time to

future production targets, assembly systems require increased capacity and functionality for ramp-up and model change respectively. There is also a general requirement to reduce NRC and lead time of assembly systems. Assembly-related operations account for over 40% of total airframe manufacturing costs [3]. Specific Airbus targets for tooling include a target reduction of 30% in the capital expenditure on tooling at the start of a project and a 50% reduction in the lead-time for assembly tooling [2].

Rate Increase and Future Demand

The magnitude of the production rate challenge is evident when comparing current production with projected forecasts. Current production rate for Airbus single-aisle (A320 family) is 42 per month (as of February 2014). Airbus have regularly increased A320 Family production, increasing from rate 36 at the end of 2010 to rate 38 in August 2011 to rate 40 in Q1 2012 to reach 42 per month in Q4 2012 [4]. Airbus project 22,071 single-aisle aircraft by 2033 and Boeing project 25,680 single-aisle aircraft by 2033 [5], [6]. To deploy 22,071 aircraft between 2015 and 2033 (18 years) requires current production to increase from Rate 42 to Rate 102. Shown by the simple calculation below and presented in Figure 1.



Source: Airbus Global Forecast 2014-2033 [6]

Figure 1. Comparison of current production rate and projected production rate for single-aisle aircraft

This calculation considers an immediate rate increase to 102 aircraft to produce the single-aisle aircraft expected in-service in 2033. However, this is extremely unlikely given the limitations of commissioning current assembly systems. The actual rate is likely to be higher because of the unpredictable nature of demand, new efficient models and backlog caused by time-to-market. Figure 2 presents a typical scenario of projected demand contrasting with actual demand.

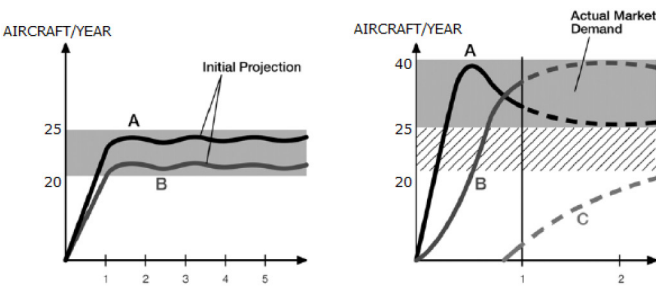


Figure 2. Comparison of typical projected demand versus actual demand (Adapted from Koren & Shpitalni 2010). Actual demand is significantly higher for aircraft (A and B) and a third model (C) is introduced earlier into the market [7]

Considering the current production rate and the future production forecast, future capacities must be capable of at least 102 aircraft per month. A radical change in approach to assembly system design is needed to meet future production rates and reductions in expenditure where an assembly system can adapt to market changes in demand and aircraft type.

Future Trends: Reconfigurable Manufacturing

Koren and Shpitalni provide succinct definition of reconfigurable systems: ‘Current research suggests Reconfigurable Manufacturing Systems (RMS) as the next generation of systems which are designed from the outset for change in function or capacity. RMS combine the advantageous characteristics of Flexible Manufacturing Systems and Dedicated Manufacturing Lines (DML), presented in Table 1. FMS have the flexibility to switch between product variants in manufacturing, but are not as cost effective as DMLs. By contrast, a DML is marked by high productivity but no flexibility. A RMS combines the advantages of both types. Not only is it cost effective with flexible production capabilities, but its structure also can be changed at both the system level and the machine level, so it can handle unexpected market changes’ [7], [8]. Reconfigurable Assembly Systems (RAS) are a subset of RMS embodying the same principles. A RAS is specifically designed to have a changeable structure which provides scalability and part family customisation capabilities to provide exactly the capacity and functionality needed when needed.

Table 1. RAS combine features of dedicated and flexible systems

	Dedicated	RMS/RMT	FMS/CNC
System Structure	Fixed	Adjustable	Adjustable
Machine Structure	Fixed	Adjustable	Fixed
System Focus	Part	Part Family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customised	General
Simultaneously Operating Tools	Yes	Yes	No
Productivity	Very High	High	Low
Lifetime Cost	Low for a single part when fully utilised	Medium or production at medium to high volume new parts and variable demand during system lifetime	Reasonable for simultaneous production of many parts (at low volume); otherwise - High

Source: Adapted from Koren & Shpitalni 2010 [7]

RMS and RAS incorporate six core characteristics. Customisation, Scalability and Convertibility are essential characteristics for RMS. For a system to be considered reconfigurable, the system must be

Customisable and Scalable or Customisable and Convertible [9]. Descriptions of essential characteristics for RAS are presented in Table 2 with aerospace examples. Modularity, Integrability and Diagnosability enable and support the efficiency of RMS, described in Table 3. 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 2. Essential characteristics for RAS Design

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. Convertability 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 [7]

Table 3. Enabling characteristics of RAS Design

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 [7]

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 duplicated and added to individual processes 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 3 presents an example of automation which is redeployed across several wing fixtures to perform drilling operations.



Figure 3. Automated drilling equipment is moved between wing fixtures [10]

A similar concept is presented in Figure 4. Recent advances in robot technologies report increased positional accuracy feasible for airframe assembly [11], [12]. Robot systems are generally cheaper than bespoke design automation which means reconfigurability is becoming more cost-effective. Figure 5 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 [13]. 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 4. Wing assembly system with mobile automated drilling and bolting system [14], [15]



Figure 5. Mobile robot platform [16]

Enabling Technologies: Customisation & Flexibility

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 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 6.



Figure 6. Robotic System and mobile robot platform [13]

Similarly, tooling pickups can be changed for different model geometries, presented in Figure 7. 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 8 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.

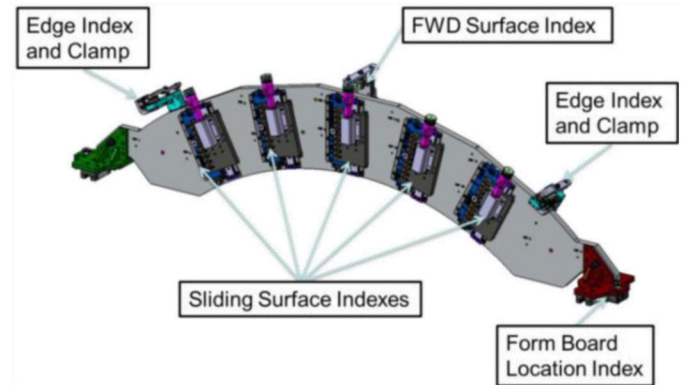


Figure 7. Flexible tooling customised for part family consisting of 17 different Forward, Mid, Aft and Tail fuselage panels [17]



Figure 8. Industrial use of Hexapods and Boxjoint system configured for airframe assembly [18]

RECONFIGURABLE ASSEMBLY SYSTEM DESIGN

Current aerospace assembly fixturing and automation systems possess the necessary characteristics of scalability and customisation for a RAS. Despite the technical feasibility of using scalable automation and flexible tooling, these systems are not integrated in such a way that a system can be reconfigured for demand changes in rate and models. A RAS should have just enough specific capability to provide exactly the capacity and functionality needed rather than general flexibility of FMS. This means the system needs to be designed specifically for the application. The requirements of the application should inform the design process to optimise the level of scalability and customisation to maximise utilisation for minimum cost. A design method is needed to systematically specify where the scalable and customisable capabilities are needed in the system.

The current aerospace assembly system design methods were found to be mostly heuristic by nature. The process usually begins with a strategic decision based on target markets which contains basic constraints which is passed to the engineering team. Information is passed between design teams with very little context and rationale for high-level decisions. Design of a static assembly system is an inherently complex process and transitioning to reconfigurable design further adds to the complexity. Despite the increase in complexity few formal design methodologies exist to support RAS design [19]. A design methodology is a process; structured to manage complexity and systematically develop a solution to satisfy goals [20]. Thereby maximising chances of success and reducing the amount of design iterations. The design of a RAS for aerospace has a unique set of challenges that a methodology should address. The design methodology needs to be capable of incorporating reconfigurability principles and fit the constraints of the aerospace industry. Aerospace assembly has unique design challenges because of process certification and complex company operations. To select a suitable methodology a basic set of criteria was derived from observations and discussions at Airbus and The University of Nottingham, outlined below.

Aerospace RAS Design Methodology Requirements

1. Design from the outset to change system capacity and function
2. Translate specific customer application requirements into physical designs
3. Design the system architecture to be independent for reconfigurability
4. Capitalise on designer knowledge and experience
5. Maximise incorporation of R&D and lessons learnt into the design
6. Combine novel and existing solutions but remain open to new ideas
7. Consider lifecycle of immature product designs and immature technologies
8. Provide structure to the system design data to be manageable and consistent
9. Plan and test reconfiguration scenarios to estimate operational impact of reconfiguration
10. Generate concepts early in design phase to estimate factory planning such as RC. vs. NRC and factory footprint

LITERATURE REVIEW OF METHODS

Some of the most popular system design methods are reviewed and assessed for suitability for RAS design. Design methods are examined for general strengths and weaknesses (Table 4). Each method is then assessed for satisfying RAS design methodology requirements. Axiomatic Design is a hierarchical design method which analyses customer needs which are systematically translated into physical designs [21], [22]. Design Structure Matrices (DSM) are a system modelling method used to represent interactions between elements comprising a system. DSMs are used to represent many different complex systems for design and analysis [23], [24]. Multiple DSMs can be combined to create Multiple-Domain Matrices (DMM) which show the interactions between domains [25]. QFD is a method to transform qualitative customer requirements into quantitative parameters and to achieve the design quality in subsystems and component parts, and ultimately to specific elements of the manufacturing process [26], [27]. Product, Process, System (PPS) is a framework for integrated modelling of manufacturing systems. PPS is used to organise manufacturing information into a common format for consistency for use with different methods and tools [28], [29]. Multiple Criteria Decision Making methods (MCDM) are a category of methods which rationalise decision making for conflicting criteria using data which is both qualitative and quantitative. Commonly used methods are Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) which have been applied to manufacturing system design [30], [31]. Taguchi method is a statistical approach to design that emphasizes the roles of research and development, product design and product development for controlling quality [32]. Design for X is a method of applying specific design guidelines for a particular issue or characteristic such as manufacture or assembly [33]. Popular examples are Design for Assembly (DFA) and Design for Automated Assembly [34]. Both of which are particularly beneficial to aerostructure assembly. Design for Changeability (DfC) focuses on incorporating changeability into a system's architecture in order to enable for foreseen and unforeseen changes within the architecture throughout the systems lifecycle. [35].

RAS Design Methodology

Despite the strengths and success of these methods, a single method cannot be applied efficiently for aerospace RAS design because of the disparate array of requirements for effective technical innovation and pragmatic application. However, novel application of several existing design methods is envisaged to satisfy the diverse requirements for aerospace RAS design. AD and DSM are selected because the strengths and weaknesses are mutually complementary [19], [36], [37]. PPS is selected to structure the information for analysis and interpretation. Some form of knowledge capture has to be included as part of the design process because none of the methods provide sufficient basis for capitalising on existing knowledge and solutions. Finally, DfC is used to incorporate scalable and customisable principles into the design process. Table 5 presents which design methods accede to specific requirements. The methods interact in multiple ways to form a complete method. The interactions of the design methods are structured both for design and to ameliorate the design process. MCDM methods are rejected on the basis of limited application to technical innovation and Taguchi method is rejected for

lack of system interaction modelling. Other Design for X methods are discounted because they lack a systems approach but are ideally suited to improving the manufacturing and assembly processes of aerostructures which enables a more cost-effective RAS by standardising assembly.

RESEARCH APPROACH

An aerospace case study is used to demonstrate how the methodology might be applied. The case study uses an existing single-aisle wing design and the production rates presented in Figure 1. The specific process is assembling ribs to spars. An overview of the methodology is provided to describe how the combined methods interact. The practical steps of the methodology are explained using the case study. The methodology is validated for RAS design by simulating an example rate increase.

RAS DESIGN METHODOLOGY OVERVIEW

An overview of the methodology is presented in Figure 9 which consists of Inputs, Design Process and Outputs. The Design Methodology integrates AD, DSM, PPS, scalability and

customisability design principles to translate customer needs explicitly to physical designs. The methodology uses knowledge captured from the customer as the Inputs for the Design Process so customer needs are embodied in the solution (Outputs).

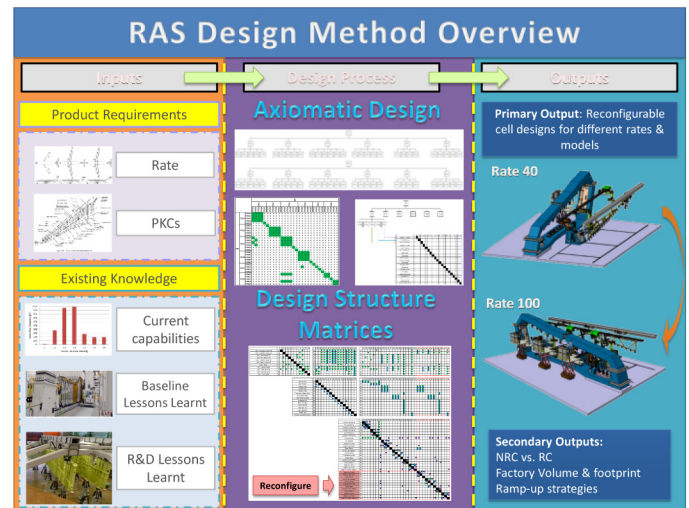


Figure 9. Overview of RAS Design Method

Table 4. Review of existing design methods and tools for RAS design

Method	Strengths	Weaknesses
Axiomatic Design	1. Suited to creative design 2. Scientific basis for design 3. Relates requirements to physical solutions 4. Design process highlights dependencies	1. Solution-neutral design process is not suitable for problems that need to combine existing solutions 2. Does not specify how physical solution should be integrated
DSM	1. Shows dependencies/independencies 2. Useful for design and management 3. Shows interactions between system elements and visualises changes 4. Simple to apply and applicable/adaptable to many scenarios	1. Elements are not traceable to requirements 2. Not suitable for creative design – difficult to use for innovation 3. Used on existing products not concept design
QFD	1. Customer driven process – designs derived from analysis of customer needs 2. Streamlined process minimises design iterations	1. Focus is on quality - limited consideration of costs and factors such as strategy, product lifecycle and emerging technologies 2. Assumes customer requirements do not change
PPS	1. Formal approach to manufacturing system representation	1. Not suitable for creative design – requires another method
MCDM (AHP, TOPSIS, etc)	1. Good for high-level decision making 2. Uses qualitative and quantitative data 3. Uses incomplete data	1. Not suitable for detailed technical solutions
Heuristic approach	1. Capitalise on tacit knowledge and experience – generally an excellent source of information 2. Useful when no analytical method exists 3. Time-saving relative to other methods	1. Difficulty in dealing with complexity 2. Dependent on designer skill and knowledge 3. No guarantee of a solution 4. Traceability may not be captured 5. Risks being subjective not objective
Taguchi method	1. Statistical method suitable for optimising technical parameters, particularly for quality control 2. Applicable to existing processes	1. Does not account for design interactions 2. Not suited to support system design integration 3. More suited to checking and improving an existing design
'Design for X' methods (DfC, DFMA, DFSS)	1. Easily applicable general design principles	1. Not a system design method - must be used with another method

Table 5. Combined methods satisfy RAS design methodology requirements

Criteria	Knowledge Capture	PPS	AD	DSM	DfC
1. Design from the outset to change system capacity and function	✓	×	✓	×	✓
2. Translate specific customer application requirements into physical designs	×	×	✓	×	×
3. Design the system architecture to be independent for reconfigurability	×	×	✓	✓	✓
4. Capitalise on designer knowledge and experience	✓	×	✓	×	×
5. Maximise incorporation of R&D and lessons learnt into the design	✓	×	×	×	×
6. Combine novel and existing solutions by remaining open to new solutions and novel ideas	✓	×	×	✓	×
7. Consider lifecycle design for immature product designs and immature technologies	✓	×	×	✓	×
8. Provide structure to the system design data to be manageable and consistent	×	✓	×	✓	×
9. Plan and test reconfiguration scenarios to estimate operational impact of reconfiguration	×	×	×	✓	×
10. Generate concepts early in design phase to estimate factory planning such as RC. vs. NRC and factory footprint	×	×	×	×	×