

Axiomatic Design of a Reconfigurable Assembly System for Primary Wing Structures

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ABSTRACT

Aerospace assembly systems comprise a vast array of interrelated elements interacting in a myriad of ways. Consequently, aerospace assembly system design is a deeply complex process that requires a multi-disciplined team of engineers. Recent trends to improve manufacturing agility suggest reconfigurability as a solution to the increasing demand for improved flexibility, time-to-market and overall reduction in non-recurring costs. Yet, adding reconfigurability to assembly systems further increases operational complexity and design complexity. Despite the increase in complexity for reconfigurable assembly, few formal methodologies or frameworks exist specifically to support the design of Reconfigurable Assembly Systems (RAS).

This paper presents a novel reconfigurable assembly system design framework (RASDF) that can be applied to wing structure assembly as well as many other RAS design problems. The framework is a holistic, hierarchical approach to system design incorporating reconfigurability principles, Axiomatic Design and Design Structure Matrices. The rationale for the framework is developed from a literature review of case studies, academic research, system design methods and industry requirements. The framework and surrounding discourse is presented in such a way that this paper can be used as a reference guide to design RAS for aerospace structures and for future research into RAS design.

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INTRODUCTION

There is an ongoing requirement within aerospace manufacturing to reduce non-recurring costs (NRC), decrease time-to-market, improve capability and increase flexibility [1]. One viable solution is to apply the reconfigurability paradigm to the assembly system so that capacity and functionality adapt to suit demand as the market changes. Jefferson *et al* reviewed the applicability of Reconfigurable Assembly Systems (RAS) as a feasible solution to aerospace assembly and reiterated current system issues and future system demands which are repeated here for reference [2].

Current System Issues

The basic system deficiencies are summarised as follows:

- Unresponsive to demand fluctuations
- Costly and prolonged ramp-up
- Product change has costly impact and slow execution
- Disruptive events severely impact production rate
- New technology implementation has similar negative impact
- Fixtures are not suitable for multiple wing sizes
- Processes are labour-intensive and slow

Future System Demands

The basic system requirements for cost-effective wing assembly are summarised as follows:

- Agile response to change
- Efficient, cost-effective rapid ramp-up and ramp-down in response to demand fluctuation and product variation
- Scalable and convertible assembly fixtures for production of entire wing part family
- Flexible customisation of fixtures for product change and variation
- Expedient design and modification
- Improve quality
- Accept changes

RAS embody many of these future system requirements but the potential benefits of a RAS are yet to be fully realised in industry. Thus, indicating that the reconfigurability paradigm still requires development to be established as a viable option for aerospace assembly.

Reconfigurability and Flexibility for Assembly: Definitions

There are several definitions of manufacturing flexibility in academia and industry used since the 1980s [3].

Reconfigurable manufacturing is a similar term established in 1999 as a new paradigm which combines the high throughput of dedicated manufacturing and the diverse functionality of flexible manufacturing systems (FMS) [4]. The difference between a FMS and Reconfigurable Manufacturing System (RMS) is that a FMS has fixed capacity and functionality while the capacity and functionality of RMS changes over time as the system reacts to changing market needs [4]. Therefore, this document will use the following definitions for reconfigurability and flexibility.

Manufacturing flexibility:

'the ability to change or react with little penalty in time, effort, cost or performance' [3].

Reconfigurable Assembly Systems (RAS) are a subset of RMS and therefore possess the same characteristics [5]. RMS and RAS are defined as follows:

'A RMS or RAS is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements' [5].

Reconfigurable Assembly System Design

To fully utilize the benefits of reconfigurable tooling and flexible automation, greater integration should be employed during the design phase. This can be done ad hoc but the integration of even fixed systems is a complex process. Therefore, the integration of reconfigurable systems will certainly require a comprehensive and systematic approach.

The aim of this paper is to make an academic contribution towards a RAS design methodology that could be used to design a RAS for aerospace structures as well as general RAS design problems.

RAS DESIGN FOR AEROSPACE APPLICATIONS: STATE-OF-THE-ART REVIEW

This paper presents an ongoing body of research into RAS design for aerospace applications and primary wing structures in particular. The paper is organized into three main sections. The first section reviews the current state-of-the-art of RAS for aerospace and outlines the barriers to implementation.

Secondly, current design theory practices suitable for RAS are presented and discussed. The final section presents a design framework for RAS with consideration of primary wing structures assembly.

RECONFIGURABLE ASSEMBLY SYSTEMS FOR AEROSPACE

This section outlines the current state of RAS in aerospace and highlights some of the key barriers that are preventing full-scale systems realizing the comprehensive market advantages of RAS.

RAS Applications in Industry and Academia

There is a growing body of work published on RAS and applications in aerospace manufacturing. Particularly, reconfigurable tooling and flexible automation [1], [6], [7], [8], [9], [10], [11]. Figures 1, 2, 3 show example reconfigurability and flexibility projects. Jefferson *et al* reviewed the feasibility of RAS for primary wing structures and concluded that technologies are readily available for implementing RAS [2]. The work highlighted the lack of design methodologies for RAS. This presents a significant barrier to realizing a RAS since a RAS 'is *designed at the outset* for rapid change in structure, in order to quickly adjust production capacity and functionality' [5]. This is cited as a reason why a RAS is yet to be used at production-scale.

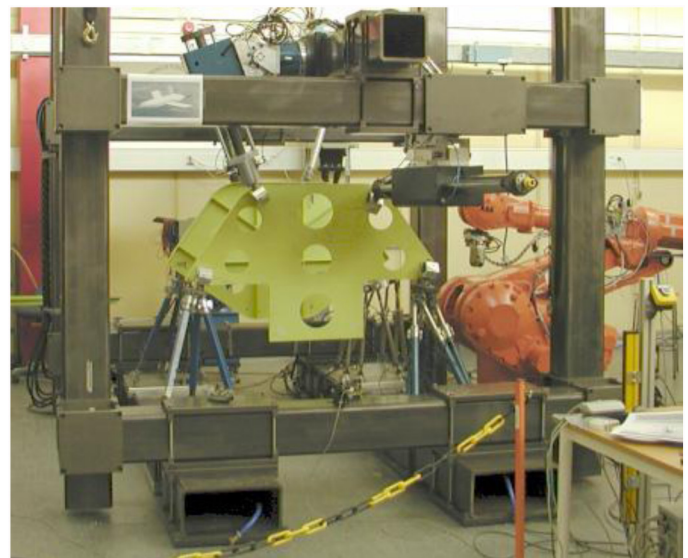


Figure 1. Affordable Reconfigurable Tooling (ART) demonstrator for low cost automation for aircraft assembly [12]



Figure 2. Reconfigurable fixture for stage one primary structures [13]

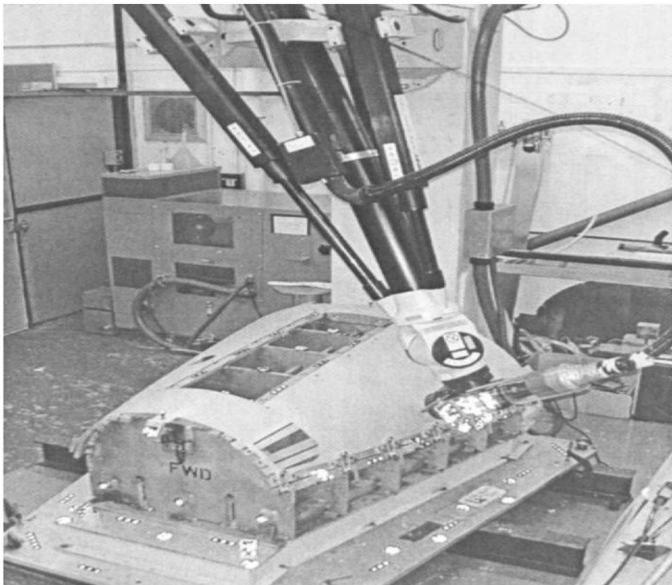


Figure 3. Flexible automated system for machining and drilling [14]

Design of Reconfigurable Assembly Systems

A RAS requires a definitive business case where there is a justified cost saving in using a RAS since RAS can require extra design time. This extra resource required to design a RAS is amplified by lack of straightforward, handbook-style RAS design methodologies.

As yet, there are few formal design methodologies and frameworks for designing RAS cited by Bi *et al*: 'A systematic design methodology is still lacking' [15]. Most current methodologies for RAS are algorithmic and do not offer principles or tools to aid the designer. Furthermore, existing RAS are designed intuitively without a formal approach [1], [7], [12], [13], [15].

Barriers to Implementing RAS for Aerospace Applications

Bi *et al* state that 'the RMS concept is not a complete solution for a manufacturing enterprise to meet all of the challenges, it is promising to take advantages of other technologies in an RMS. For example, the concept of Lean Production' [15]. Another barrier to implementing RAS is 'how to help an enterprise evolve from a non-configurable system to a reconfigurable system. It is worth to note that system reconfigurability can be achieved by manipulating a set of non-configurable systems at the management level' [15]. This is also pointed out by Jefferson *et al*: 'Current issues of responsiveness aren't solved by a standalone RAS. Research suggests that to reduce costs and increase agility using RMS, businesses need to consider the enterprise as a whole.'

Summary

RAS offer potential to meet ongoing requirements but several significant barriers must be overcome. Since the RMS paradigm was introduced by Koren in 1999, [4] there has been limited adoption of RAS, evidenced by limited uptake in industry [2], [5], [15], [16]. There is also a lack of formal methodologies that suit RAS design [15].

Current Practices in Design Theory

This section presents some of the research advances in system design theory and critiques their suitability for RAS design.

Design Theories Suitable for RAS Design

RAS should embody a systems approach to design [4]. Therefore, design methodologies that are not system-based can be ignored for the purpose of this research which is to develop RAS design methodologies. There are several system design methodologies but this research focuses on Axiomatic Design (AD) and Design Structure Matrices (DSM). AD is a scientific approach to design which hypothesizes that design is governed by fundamental principles. DSMs are used to model system interactions, which is undoubtedly critical to RAS design. This research is limited to these two approaches. Suh posits that all good design theories are consistent with the axioms of AD and as such have not been considered as part of this research [17], [18]. The House of Quality method [19] shows most similarity to AD but Suh states that the 'House of Quality method is for existing products not for conceptual designs which require a solution-neutral environment' [18]. Hence, the aim is to investigate how a suitable RAS design methodology might be developed.

Axiomatic Design Theory

Axiomatic Design (AD) provides systematic and scientific basis for making design decisions [20]. Suh posits that there are fundamental principles that govern good designs [17, 18]. These are expressed as two axioms.

Axiom 1: Maintain the independence of the functional requirements

Axiom 2: Minimize the information content of the design

The design world involves an interplay between 'what we want to achieve' and 'how we choose to satisfy the need (i.e. the what)'. The AD framework organizes this design world into four domains: Customer, Functional, Physical and Process Domains [17]. Figure 4 shows the four design domains and the zigzagging process to decompose the design problem. Tang et al and Guenov & Barker provide reasonable descriptions of the method, portions of which are duplicated exactly here:

[Tang et al state] The AD method proceeds from a high level of abstraction to detailed design elements (i.e., from meta-product systems to assemblies to components to features to parameters). This activity of definition and detailing produces a prescriptive model of design hierarchy for the design entity in each of three domains: functional, physical, and process. The decisions that are made at higher levels affect the statement of the design definition at lower levels. That is, the design team goes through a process whereby they zigzag between domains to decompose the design problem. At a given level of design hierarchy, there exists a set of function requirements (FRs) defined as the minimum set of requirements needed at that level. The definition of FRs depends on the solutions with design parameters (DPs), namely, defining acceptable FRs may involve several iterations. Before zigzagging FRs, the corresponding hierarchical level DPs shall be selected. Once a corresponding DP can satisfy a FR, a focused FR can be decomposed into a set of lower-level requirements. The design team will develop different solutions for each DP to satisfy a FR and select the best alternative at each hierarchical level according to axiom 1 and axiom 2. [20].

[Guenov & Barker state] Axiom 1 requires that Functional Requirements (FRs) be independent of one another, which enables each FR to be satisfied *without* affecting any of the other FRs. Thus there is no coupling of function where it can be avoided, and the design remains as uncomplicated as possible. Axiom 2 provides a quantitative measure of the merits of a given design, and thus it is useful in selecting the best among the designs which satisfy axiom one [Suh, 2001]. Generally, the design that uses the least information is superior. This is explained in more detail later in this section. According to the ADT, the design process takes place in four domains (Fig. 2, adapted from Tate [1999] and Suh [2001]): Customer, Functional, Physical and Process. Through a series of iterations, the design process converts customer's needs (CNs) into Functional Requirements (FRs) and constraints (Cs), which in turn are embodied into Design Parameters (DPs). Functional Requirements can be defined as "a minimum set of independent requirements that completely characterises the functional needs of the product in the functional domain"; Design Parameters are "the key physical variables in the physical domain that characterise the design that specifies the FRs" [Suh, 2001, p 14]. DPs determine (but also can be affected by) the manufacturing or Process Variables (PVs). The decomposition process starts with the decomposition of the overall functional requirement-in practice this should

correspond to the top system requirement. Before decomposing a FR at a particular hierarchical level in the functional domain, the corresponding DP must be determined for the same hierarchical level in the physical domain. This iterative process is called zigzagging (see also Tate [1999] for a more thorough treatment of the decomposition problem). Zigzagging also involves the other domains since manufacturing considerations may constrain design decisions, while "over-specified" requirements could virtually prohibit the discovery of feasible design solutions [21].

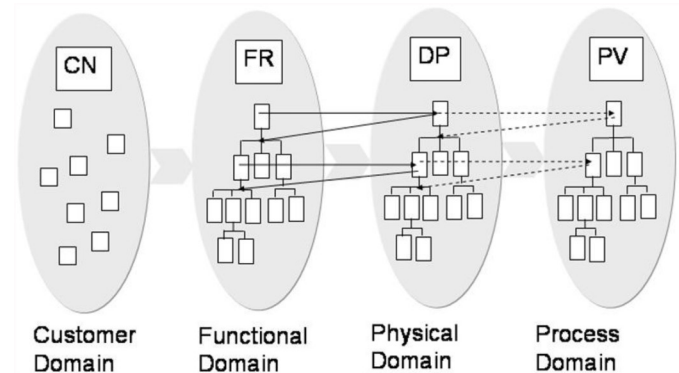


Figure 4. The four design domains [21]

Once a corresponding set of FRs and DPs is developed, a Design Matrix (DM) is created. Figure 5 shows the three possible design outcomes which are uncoupled, decoupled and coupled. Tang et al explain how the resulting DM provides one of three different design outcomes:

Depending on the type of resulting DM, three types of designs exist: uncoupled, decoupled and coupled. Regarding the uncoupled design, each FR is satisfied by exactly one DP, and the resulting DM is diagonal. Axiom 1 is fully satisfied with the uncoupled design. The decoupled design occurs when the DM is lower triangular, which means that a sequence exists, where by adjusting DPs in a certain order, the FRs can be satisfied. The DM of a coupled design contains mostly non-zero elements and thus the FRs cannot be satisfied independently [20].

Figure 5 shows the three types of design that occur from the DM. A coupled design forms feedback loops which dramatically increase complexity. The tolerance should be reduced or the design changed to reduce or eliminate the coupling effect [18].

	DP ₁	DP ₂	DP ₃
FR ₁	X	O	O
FR ₂	O	X	O
FR ₃	O	O	X
Uncoupled System			

	DP ₁	DP ₂	DP ₃
FR ₁	X	O	O
FR ₂	X	X	O
FR ₃	X	X	X
Decoupled System			

	DP ₁	DP ₂	DP ₃
FR ₁	X	X	O
FR ₂	O	X	O
FR ₃	O	X	X
Coupled System			

Figure 5. The three Design Matrix (DM) outcomes [22]

Applying AD to manufacturing systems has been investigated and published [23]. Research on AD of flexible manufacturing systems has also been published [24].

Axiomatic Design for RAS

The elicitation of customer requirements and mapping to physical parameters shows strong potential for RAS but appears largely un-researched in academia and industry.