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Reducing the Acquisition Cost
of the Next Fighter Jet using Automation

by

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A thesis submitted in partial fulfilment of the
requirements for the degree of
Doctor of Engineering (Int.)

University of Warwick, Faculty of Science, WMG

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Declaration

This innovation report is submitted to the University of Warwick in support of my application for the degree of Doctor of Engineering (International). It has been composed by myself and has not been submitted in any previous application for any degree. The work presented (including data generated and data analysis) was carried out by the author.

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University of Warwick

Abstract

The acquisition cost of fast-jets has increased exponentially since WWII, placing defence budgets under severe pressure. Fleet sizes are contracting as fewer new aircraft are ordered, and with new programmes few and far between the methods of assembling airframes have hardly changed in fifty-years. Modern airframes rely on traditional welded steel assembly fixtures and high accuracy machine tools, which represent a significant non-recurring cost that cannot be reconfigured for re-use on other programmes.

This research investigates the use of automation to reduce the acquisition cost. Its aim is to demonstrate innovations, which will collectively assist in achieving the twin goals of Tempest, to be manufactured 50-percent faster and 50-percent cheaper, through the re-configuration and re-use of automation, creating a flexible factory-of-the-future.

Two themes were explored, the UK-MOD's acquisition process, to position this research in the timeframe of the next generation of fast-jet, and the use of automation in airframe assembly globally, specifically focusing on Measurement Assisted Assembly (MAA), part-to-part methods and predictive processes. A one-to-one scale demonstrator was designed, manufactured and assembled using MAA; and from the measurement data additively manufactured shims for the structure's joints were produced.

The key findings are that; metrology guided robots can position parts relative to one-another, to tolerances normally achieved using welded steel fixtures, maintaining their position for days, and can then be reconfigured to assemble another part of the structure.

Drilling the parts during their manufacture on machine tools, using both conventional and angle-head tooling, enables them to be assembled, negating the requirement to use traditional craft-based skills to fit them. During the manufacture of the parts, interface data can be collected using various types of metrology, enabling them to be virtually assembled, creating a Digital Twin, from which any gaps between parts can be modelled and turned into a shim using an additive manufacturing process with the limitation that current AM machines do not produce layers thin enough to fully meet the shimming requirement.

The acquisition process requires, a technology to be demonstrated at technology readiness level (TRL) 3 during the concept phase, and have a route-map to achieve TRL 6 in the development phase, following the assessment phase.

The novel use of automation presented in this thesis has the potential to enable manufacturing assets to be re-configured and re-used, significantly reducing impacting the acquisition costs of future airframe programmes.

Collectively the innovations presented can significantly reduce the estimated 75 percent of touch labour costs and 9 percent of non-recurring costs associated with assembling an airframe. These innovations will help to enable a digital transformation that, together with other Industry 4.0 technologies and methods, can collectively enable the automated manufacture of customised aerospace products in very-low volumes. This is of relevance not only to next generation fighter jets, but also to emerging sectors such as air-taxis.

Acronyms

ABS	Acrylonitrile Butadiene Styrene
ACC	Air Combat Cloud
ADFAST	Automation for Drilling, Fastening, Assembly, Systems integration and Tooling
AFT	Automated Flexible Tooling
AGP	Aerospace Growth Partnership
ALCAS	Advanced Low-Cost Aircraft Structures
AM	Additive Manufacturing
AMM	Assemble-Measure-Move
AOG	Aircraft on the Ground
ARC	Adaptive Robot Control
ART	Affordable Reconfigurable Tooling
ASO	Assembly Sequence of Operations
ATI	Aerospace Technology Institute
BAE	BAE Systems plc
BEIS	Department for Business, Energy & Industrial Strategy
CADMID	Concept, Assessment, Demonstration, Manufacture, In-Service & Disposal
CASLCM	Conventional Air-Launched Cruise Missiles
CALM	Centre for Additive Layer Manufacture
CDR	Critical Design Review
CMM	Coordinate Measuring Machine
CoS	Condition of Supply
CPS	Cyber-Physical Systems
CPS	Cardinal Points Specification
CRD	Common Requirements Document
CTO	Chief Technology Officer
DfM	Design for Manufacture
DoD	Department of Defence
DPOC	Deep and Persistent Offensive Capability

EMD	Engineering and Manufacturing Development
F-35	Joint Strike Fighter - F35
FA ³ D	Future Automated Aircraft Assembly Demonstrator
FAL	Final Assembly Line
FAUB	Fuselage Assembly Upright Build
FCAS	Future Combat Air System
FCAS TI	Future Combat Air System Technology Initiative
FCBA	Future Carrier Borne Aircraft
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
FFF	Fused Filament Fabrication
FiaD	Factory in a Day
FJCA	Future Joint Combat Aircraft
FLAM	Fixtureless Assembly Manufacture
FMS	Flexible Manufacturing System
FOAS	Future Offensive Air System
GDP	Gross Domestic Product
HVMC	High /value Manufacturing Catapult
IAAD	Integrated Autonomous Assembly Demonstrator
IOC	Initial Operational Capability
IoT	Internet of Things
IPT	Integrated Project Team
JCS	Joint Concept Study
JSF	Joint Strike Fighter
KPI	Key Performance Indicators
LIMA	Laboratory for Integrated Metrology Applications
LoB	Lines of Business
LOCOMACHS	Low Cost Manufacturing and Assembly of Composite and Hybrid Structures
MAA	Measurement Assisted Assembly
MADA	Measurement Assisted Determinate Assembly

MARA	Metrology Assisted Robot Automation
MAI	Military Aircraft & Information
MBD	Model-based Description
MBE	Model-based Enterprise
META	Metrology Enhanced Tooling for Aerospace
MMC	Move-Measure-Correct
MoD	UK Ministry of Defence
NAO	National Audit Office
NGF	Next Generation Fighter
OEE	Overall Equipment Effectiveness
OML	Outer Mould Line
P2P	Part-to-Part
PLM	Product Lifecycle Management
PMA	Post Module Assessment
PMI	Process and Manufacturing Information
P&S(UK)	Platform & Services (UK)
RAF	Royal Air Force
RAMI4.0	Reference Architecture Model Industrie 4.0
RAS	Reconfigurable Assembly Systems
RC	Remote Carrier
ReFlex	Reconfigurable Flexible Assembly Tooling
RFA	Robotic Fixtureless Assembly
RFP	Request for Proposal
RIM	Resin Infusion Moulding
RMS	Reconfigurable Manufacturing System
RUSI	Royal United Services Institute
SAE	Society of Automotive Engineers
SCAF	Système de Combat Aérien Future
SDR	Strategic Defence Review
SDSR	Strategic Defence & Securities Review
SECF	Special Engineering Composite Facility

SLOC	Source Lines of Code
SLS	Selective Laser Sintering
SoS	System of Systems
SPI	Smart Procurement Initiative
SUAV(E)	Strategic Unmanned Air Vehicles (Experiment)
TRL	Technology Readiness Level
TSM	Technical Standards Manual
UAV	Unmanned Aerial Vehicle
UCAS	Unmanned Combat Air System
UCAV	Unmanned Combat Aerial Vehicles
UoN	University of Nottingham
VAS	Variation Simulation Analysis
VR/AR	Virtual reality / Augmented Reality
WLCC	Whole Life Cycle Cost

1 Introduction

Over the last 5 years a series of activities have been carried out for the purpose of determining the potential benefits of utilising automation for the assembly of the next generation of military aircraft, and how such automation could be best applied.

The theme of the body of work presented here is thus to look at new approaches to enable the automated assembly of the next generation of military aircraft. The achievement of this goal requires many different technologies and methods to be combined to form a coherent strategy for both the physical and digital worlds.

The life-cycle of military aircraft, including the manner in which they are costed and procured, has a significant influence on the engineering of such products, impacting on the available processes, resources, and level of investment in manufacturing facilities and systems. This work aims to look at the problem within this wider context and from these insights report on the type of automation and enabling technology and methods for future generation military aircraft manufacture.

The purchase price of modern fast-jets, such as Joint Strike Fighter (JSF) F-35, are circa £100m and their operating costs are similar over a 30-year life. This presents a huge fiscal problem to the customer; who tends to be an ally, as most defence business is undertaken through government-to-government agreements. Generally defence budgets have decreased, as a percentage of Gross Domestic Product (GDP), since the end of the cold-war and the collapse of the Berlin Wall. But in that 30-year period only two new fast-jets, Typhoon and F-35, have been produced; whilst in the previous 30-year period 27 aircraft were developed in the UK by companies merged into one organisation called British Aerospace by the Aircraft and Shipbuilding Industries Act 1977, see Figure 1, pp 2. The defence budget of NATO members is approximately 2 percent of GDP, and there is great pressure on it. In the UK the National Audit Office (NAO) has assessed how the UK Ministry of Defence (MoD), BAE's largest customer, manages the procurement budget and indicated there is a potential "black-hole" of between £4.9billion and £20.8billion.

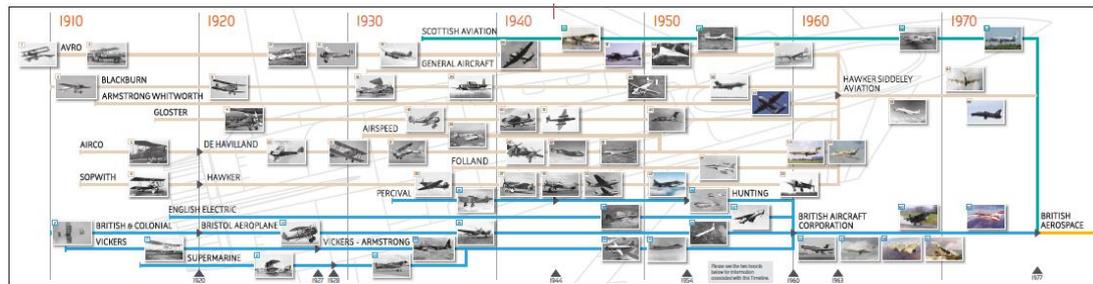


Figure 1: BAE Heritage Aircraft 1909 to 1979 (source: BAE Systems)

Every five-years the UK government sets out its approach to national security in the Strategic Defence and Security Review (SDSR). At the start of this research there was no new fast-jet programme, which was of great concern within the industry for a variety of reasons including the demographic of the workforce. The last programme, F-35, started more than two decades ago, and it takes time to develop the air vehicle and build the partnerships necessary to produce it. In 2018, mid SDSR cycle, Tempest was unveiled at the Farnborough International Air Show. From the start the customer's vision was rapid delivery and affordability, as a flexible and agile capability, configurable for a range of future conflicts. Replacing the Typhoon fleet in 2035, there is considerable pressure to go from concept to in-service in about half the time Typhoon took. Hence alternative ways are needed to deliver the aircraft quickly at an affordable cost.

BAE's enthusiasm for using robotics and automation, and its recognition of the potential benefits derives from recent installations such as automated countersinking; a cell which countersinks 66 carbon parts using two collaborating robots, and six reconfigurable holding frames.

The work presented within this innovation report primarily addresses a method of assembling the airframe of a fast-jet, using a combination of metrology and robotics.

The specific challenges include:

- A craft based industry
- Very low volumes
- High tolerances
- A typical make-span of three-years
- The compartmentalisation of projects
- The demographic of the workforce

- Design suited for traditional fixture
- Learning curves

The last project, JSF F-35, is the largest defence project in history, and the technology BAE System developed and uses was designed to manufacture over 3500 aircraft at a rate of 1-per-day, for many decades. The next generation fast-jet will replace less than 200 Typhoon aircraft, the size of the UK fleet, and the overall volume of aircraft needed, even with partners on the projects, will be under 1000. Two costs on the F-35 programme which are considered by both BAE Systems and the MoD as unaffordable by the next generation fast-jet, with such low numbers, are the non-recurring costs and inflexibility of the machine tools and monolithic steel fixtures needed to assemble the airframe.

Predictive shimming using additive manufacture, determinate drilling at the detail manufacturing stage, and metrology guided robots, have been combined to increase knowledge and address a key problem, namely the automation of a very low volume product through reuse.

The conclusions and the processes developed in partnership have been shown to both BAE and DSTL on full size demonstrators, and is presented in Chapter 6.

1.1 Research Objectives

Major barriers to the use of flexible automation exist in relation to traditional inflexible assembly fixture and large machine tools, (Muelaner et al., 2011a). Moving forward the adoption of new processes which eliminate the need for them, would be a significant enabler for automated assembly, since they would make the product affordable to the customer.

The primary research objectives are therefore to determine the practicality of replacing traditional assembly fixtures with a reusable, reconfigurable robotic system, and negating the use of high-accuracy, very expensive machine tools. These objectives fit with the company's manufacturing vision, and their outcome will influence future investment strategies.

There is no single solution for each objective, rather they will be achieved through a collection of smaller innovations. Collectively they represent a paradigm shift in

airframe assembly, away from the traditional craft-based fitting methods that have been the industry norm for more than half-a-century built around “islands-of-automation” to assembly in an integrated digital world.

Reusable, reconfigurable modular tooling has been previously researched and developed by BAE (Scott et al., 2004), other aerospace companies (Kihlman and Engström, 2002), (Stone, 2004), universities (Kihlman, 2001) and SMEs (Helgesson et al., 2010), and it will be described in more detail in Section 3.2 Assembly Fixtures, pp 41.

While these fixturing systems shortened the lead-time for fixture manufacture, and their use of adjustable pick-ups made from tubes and clamps enabled them to be reconfigured and accept late design changes, the reuse of the parts, seen as a key-benefit in reducing cost, was limited; particularly those that had been cut-to-length such as the beams. The systems in BAE were used on development aircraft programmes and initial low-rate production, where late-changes to a design are common, but they were not robust and that led to quality issues.

In 1990, BAe developed the automated assembly of sub-assemblies such as shear-webs and avionics trays for the Typhoon programme in a cell built around a gantry robot and an auto-drill rivet machine. The sub-assemblies were built and installed in development aircraft which flew in the test programme. However, timing rather than capability prevented it from being adopted, and the nature of programmes in the sector meant it was practically forgotten. Today the system is available using an articulated arm robot and an auto-drill rivet machine.

Twenty-years later, the presence of an automated countersinking cell based on robotics compared to a pulse-line that linked a bank of machine tools, highlighted to the company that a generic technology was now commercially available that provided the agility it sought for its manufacturing vision. This helped identify the engineering objectives.

The combined outcome of these research objectives provided BAE with sufficient confidence to invest in a Factory of the Future at its Warton site in Lancashire, details of which are published on its website (BAE Systems plc, 2020).

1.2 Portfolio and the Structure of this Report

The broad motivation and industrial requirement are discussed in this chapter. Table 1, pp 5, shows the linkage between each of the eight un-published portfolio submissions, which are part of the Eng.D, and the chapters in this report.

Submission no.	Portfolio Submission Title	Innovation Report Chapter
1	The Business Need	2
2	Defence Acquisition a Problem or an Opportunity?	2
3	The Engineering Objectives	3
3B	Metrology Assisted Assembly Literature Review	4
4	BAE Design and Manufacture Processes	5
5	Robotic Assembly of an Airframe	5
6	Meccano™ Assembly with Predictive Shimming	5
7	Eng.D International Placement at KU Leuven, Belgium	6

Table 1: Eng.D Portfolio Structure

1.2.1 Chapter 2 – The Business Need

Chapter 2, pp 17 provides a general introduction to the defence sector, it describes its uniqueness, the importance of national sovereignty and partnerships and the mega-projects that last decades and are very low volume.

The next generation air vehicle was identified as Tempest in July 2018. The chapter discusses Tempest the air vehicle, Team Tempest the collaboration between industry and the MoD that is a model of “shared equity and shared risk”, and the Combat Air Strategy; all of which were announced at the same time but are three distinct entities. Further discussion on Tempest including its predecessor, Future Combat Air Systems (FCAS), can be found in Appendix A, pp 159.

BAE has evolved as a company during the five-years that this research took. Hence Chapter 2 updates the changes to the organisation, some of which have directly impacted this research through the availability of a new funding source. The business need is considered in the context of the Team Tempest Future Combat Air System concept, see Figure 2, pp 6.

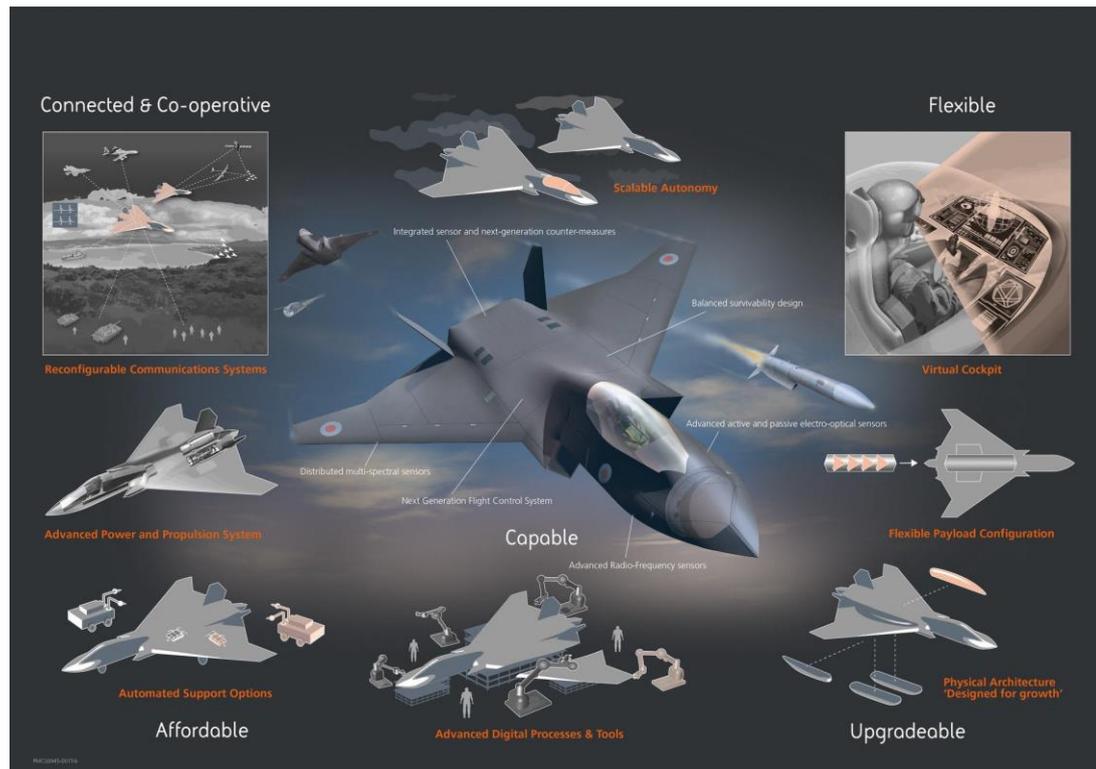


Figure 2: Team Tempest Future Combat Air System concept infographic (source: BAE Systems)

1.2.2 Chapter 3 – Current Best Practises

Chapter 3, pp 41, sets in context what would be used today if the research were not undertaken, thus identifying with the engineering objectives.

1.2.3 Chapter 4 – Current State of the Art in Airframe Assembly

Chapter 4, pp 47, provides an update to the literature review which originally focused on measurement assisted assembly (MAA) and final assembly lines (FALs), to include emerging ideas and funded programmes.

1.2.4 Chapter 5 – Progression towards Automated Assembly

Chapter 5, pp 73, discusses, in the context of the individual engineering objectives, the design, manufacturing and assembly of two demonstrators, and what was achieved in the context of this research.

1.2.5 Chapter 6 – Contribution to Innovation

Chapter 6, pp 112, initially discusses the engineering objectives in the context of the innovations that collectively provide a solution to them, and ultimately the business need.

Chapter 6 also presents a vision of the factory of the future using the innovations as a foundation.

The chapter finishes with conclusions based upon the research undertaken, and recommendations for follow-on work, some of which is currently occurring, the short-term research required, and a long-term forward look.

1.3 Methodology - Research Approach

The research initially investigated, through a review of the available literature on defence acquisition, a few of the causes for the spiralling costs to identify if it was a problem or an opportunity.

The engineering objectives, which are two large non-recurring costs for a project, were then reviewed using key publications, use-cases which have never been published before, and personal involvement, to provide an appreciation of how the current methods of assembly have evolved and the current state.

A demonstrator section of airframe was then designed at BAE in collaboration with an external research partner, who had access to a facility to assemble it. The parts were manufactured both internally and externally, and data was collected and analysed to assess the impact on the assembly. The assembly was undertaken twice, initially in an automated facility, then in a collaborative environment. The data was collected and analysed to determine if the outcome could be predicted.

The innovation report draws on the findings from the demonstrator to illustrate how the new generation of air vehicle can be assembled using automation.

The literature searches made use of the databases available to WMG Doctorial students through the library, which include Emerald, Engineering Village, IEEE Xplore, SAE Mobilus, ScienceDirect (Elsevier Science Publications), Scopus, and Web of Science, as well as general databases such as Google Scholar and Microsoft Academic. Also used were databases from publishers such as Taylor & Francis and Springer. Social networking sites like ResearchGate enable papers to be shared, and questions asked or answered. It is also possible to set-up alerts from the House of Commons related to the business of specific committees like the Defence Committee, and receive daily news reports from trade periodicals such as Aviation

Week & Defence World, newsletters like MIT Technology Review and daily briefing from Nature, as well as search forums and receive direct mailing from companies.

The research question was explored by reviewing the existing body of knowledge, using key words such as, aerospace, airframe, assembly, automation, metrology, reconfigurable, and robot.

1.4 Role and Contribution to the Research

The IAAD and IAAD1B projects were a piece of major research for BAE Systems, with the potential to significantly impact the assembly of the next generation of fast-jet. The projects in totality required the combined skills of both company employees and academics from universities and catapult centres to undertake them. The contribution of the research in this Eng.D was principally the conceptualisation and development of the ideas that formed the projects, as opposed to, the programming and operationalising of them.

The manufacturing director had a vision for the factory of the future; an environment capable of assembling non-specific airframes using unguarded mobile robots, in a data-rich environment. The contribution of this Eng.D research was to use a combination of foresight, the prospect of the assembly of the next generation of fast-jet based on metrology guided robots, and human robot interaction, as well as background know-how (knowledge) of current methods of production, in a broader context, to define a method of assembling an airframe which met the business need and engineering objectives.

This research has sought to identify the gaps and coordinate and drive a set of necessary innovations to help make this vision possible, summarised in the following paragraphs.

1. Identifying the gap; this Eng.D research identified that during part manufacture using very accurate machine tools, such as DS Technology EcoSpeed F, the inherent accuracy of the machine tool could be used to position and drill the fastener holes to tolerances of less than 0.1mm, as well as measure key-features such as interfaces with other parts. This Eng.D

research further identified that the measurement data could be used to create a digital twin of the part, and from that digital twin using an additive manufacturing process, shims could be made which enabled two parts to be accurately located relative to one another.

2. While industrial robots are repeatable, they are not accurate; however with the addition of metrology they can be guided or positioned accurately. This Eng.D research further showed a metrology guided robot with a suitable end effector, could position and hold a part in a global frame of reference, allowing it to be fastened to another part; considerably reducing the time needed to assemble the product.
3. Identifying the need to define the size of the gaps needed between parts based upon existing manufacturing capability and statistical methods. The sizes of the gaps and the use of robots in place of a traditional fixture were conveyed to the design function, for inclusion in the design of the demonstrator articles. The use of robots enabled this Eng.D research to explore different assembly sequences; which were then conveyed to the tooling designers and robot programmers.

This research co-ordinated many subgroups involved in the research, ensuring the direction and focus were maintained in order to address the overall goal in a holistic manner.

As outlined in the work, the innovations and four patent applications are evidence of state of the art ideas generated and applied, in a targeted engineering context, to the assembly of a next generation airframe.

As described in this thesis, the innovations and four patent applications are evidence of state of the art ideas, applied in an engineering context, to the assembly of an airframe.

1.5 Rational Behind the Research

1.5.1 Current Best Industry Practice

The metallic parts that make-up the structure of an airframe are located in welded steel fixtures, that are arranged in assembly halls in cells, flow-lines, or pulse-lines.

The parts are “fitted” together using craft-based skills. Either the whole fixture or part of it is portable, and moved using a combination of cranes, over-head mono-rails, or trollies and man-mover tug-trucks. A fixture is moved to a machine tool so that an interface surface can be accurately machined into a non-structural sacrificial material, for outer mould line control, and a pattern of holes can be drilled either for interchangeable (ICY) panels or through stacks of dissimilar materials for fixed-skins, to nominal CAD geometry.

1.5.2 Aspects of this Research.

There are two aspects to this research; the infrastructure and the assembly process that uses it.

The infrastructure comprises of traditional fixtures and large environmentally controlled machine tools. Used to enable the assembly process, they are viewed by the organisation as expensive non-recurring costs incurred by a project, which then has exclusive use of them. These assets are fixed and occupy the same floor space for decades, often with minimal change; the limitations of traditional fixtures are well documented, (Kihlman, 2001) (Martin et al., 2010) (Muelaner et al., 2011b). In addition, project secrecy discourages the sharing of facilities and knowledge.

The process of assembling the structure involves manually loading the parts and any measuring any gaps between them, before they are removed to have both a liquid-shim (known by its trade name Hysol™) and a release agent applied. The parts are reinstalled squeezing the shim between the interfaces; the shim is then allowed 24-hours to harden before any drilling is undertaken. The drilled parts are then removed for a second time to allow, deburring, removal of any excess cured Hysol™ and release agent, before they are installed for a final time with sealant, a promotor if required, and fastened together. A significant quantity of “craft-work” has to be undertaken to enable the fastening task to be performed; based on Bullen’s example, see Figure 6, pp 23, there is 5-times as much locating, shimming and drilling as there is fastening.

This research addresses the question of how the structure can be built without the current infrastructure and how that changes the processes required.

1.5.3 Motivation

The next generation of air vehicle might be unmanned, manned, or a loyal-wingman, with or without 6th generation features; the requirements of the air-vehicle are not yet publically available. The volumes of air-vehicles required are likely to be very-low to low, between one-offs and less than 1000 to replace existing fleets. To achieve this unprecedented potential variation the factory of the future needs to be agile, able to manufacture a mix of highly customised products, in small batches. With new programmes few and far between, this is the first in two decades, it is a “once-in-a-generation” opportunity to influence the manufacturing method for the next-decade and beyond.

1.5.4 Business Rational

Financial pressure on the UK defence budget has seen both the customer and supplier setting ambitious targets for the next fighter aircraft programme; the mantra is “50-percent faster and 50-percent cheaper”, (Hill, 2020).

The cost of developing a fighter aircraft is significant; and it is unlikely the UK could afford to undertake such a project without partners. Which type of partnership will be pursued is currently unclear, the common European approach is an IJV, such as Eurofighter Typhoon GmbH, but this is seen as overly bureaucratic, making the product more expensive.

The business sees an agile manufacturing facility as the opportunity to potentially customise late in the production sequence, as well as creating new ways of working and business models. It also wants to develop the IP, and provide it to the programme.

The machined metallic parts that the airframe is built from are almost most certain to be retained; high performance jet fighters require high-strength, light-weight, accurate parts. The machining processes have been developed to produce thin-walled, deep pocketed parts that are accurate and have minimal distortion. With the appropriate improvements, methods of drilling the fastener holes in parts at the detail-stage, to enable assembly rather than fitting, could be developed.

1.5.5 Long-term Vision

The short-term aim is to assemble, not fit-together, the parts of an airframe. In the medium-term this would provide the opportunity to create smart structures, which in

the longer-term, linked to concept of a Digital Twin, would negate the need structural test items, (Tuegel et al., 2011).

1.5.6 Research Options Available.

The options available to this research are:

- Investigate alternative machine tools,
- Replace traditional tooling with reconfigurable tooling,
- Consider alternative shimming methods such as thickness layer compensation on carbon parts, or predictive fettling of the structure,
- Use of an Additive Manufacturing process to create shims,
- Use of industrial robots, either metrology guided robots or robots with enhanced accuracy,
- Reduce the level of craft-skills required to build an airframe, and
- Alternatives to the use of air-conditioning for environmental control.

1.5.7 Research Options Not Followed

Of the options listed in Section 1.5.6, the following options were discounted in this research, with the following reasons;

- Alternative machine tools were not investigated as part of this research. If a new machine tool were required the company would create a specification for it, allowing Facilities Management to tender for its build and installation. While an alternative machine tool might be cheaper, it would not significantly change the assembly process.
- The latest literature on reconfigurable tooling, (Jonsson, 2013), is reviewed in Chapter 4, pp 47, however the company has previously developed and patented (Scott et al., 2004) a system which has been used in production. Its use has generated an opinion within the company of its suitability, which is discussed in Section 3.2 – Assembly Fixtures, pp 41.
- The company has been developing methods of controlling the outer mould-line for more than two-decades. The MAA method of predictive fettling, (Muelaner et al., 2011a), is part of the current Typhoon manufacturing process, and needs portable fixtures and machine-tools; hence is discounted,

while alternative ideas such as thickness layer compensation, (Drewett et al., 2017), is currently being considered by the carbon-fibre business.

- Finally, the environment in the current assembly halls is tightly controlled, thereby reducing the variation in build-standards, but at considerable non-recurring and recurring cost. Smart factories, and the Light Controlled Factory (Ross-Pinnock and Maropoulos, 2014), may be viable alternatives to consider but they will not provide a solution to business need and the supplier/customer target of “50-percent faster, 50-percent cheaper”. However, it is a line of investigation that should be considered post this research.

1.5.8 Gap in the Research

The literature review showed the focus for the aerospace industry was the problems it faces as it manufactures airframes with carbon-fibre skins. Chief amongst them is achieving outer-mould line control, the impact it has on aerodynamics, and the consequences such as increased fuel consumption, air pollution, etc. A number of measurement assisted assembly (MAA) methods have been proposed, (Muelaner et al., 2011a), but there is a gap in the research associated with the assembly of the structure before the skin is applied.

To address this gap and the business need, this research has chosen an innovative approach, an amalgamation of three areas:

1. The use of industrial robots, either metrology guided robots or robots with enhanced accuracy, to primarily replace the fixtures,
2. The use of an Additive Manufacturing process to create shims, to locate one part relative to another, filling any voids or gaps, and,
3. Drill all the fastener holes as the parts are manufactured, reducing the level of craft-skills required to build an airframe in the assembly halls.

1.5.9 The Research Direction

The focus of previous industrial R&D has been directed at past aircraft programmes, and most of the literature, has been in achieving an aerodynamic profile through control of the skin-to-structure joint, and eliminating the need to strip & deburr using one-way assembly.

There is little literature that discusses the design of parts with gaps between them based upon the machining process capability; the manufacture of bespoke shims using an AM process based upon measurement data collected as the part is manufactured; the drilling of fastener holes to either an interchangeable or a one-way standard; and the use of metrology guided robots to hold parts relative to each other, while the shims and fasteners are installed; this research will focus on these issues.

1.6 Key-findings

The key-findings from the research, and which will be described in the subsequent chapters are:

1.6.1 New Knowledge

In the context of this research it was demonstrated, at a one-to-one scale, that the metallic structure of an airframe could be assembled using MAA, to the tolerances expected of a traditionally assembled structure. Metrology guided robots positioned the parts in a global frame of reference using Move-Measure-correct (MCC), to an accuracy associated with a traditional welded steel assembly fixture, and they maintained those positions for days rather than the traditional few seconds.

Drilling the fastener holes in the metallic parts on the same machine tool that they were machined on, enabled different part-to-part assembly techniques to be applied, depending upon the position of the part in the assembly sequence and the parts that it interfaces with. Both determinate or interchangeable assembly and one-way assembly part-to-part assembly techniques were demonstrated, eliminating the need to manually drill on assembly, and saving up to 75% of this element of the overall cost of assembly.

By collecting measurement data while the metallic parts were being manufactured, and using basic virtual assembly techniques, additive manufacturing shim models were created. The models were then used to print AM shims for pre-assembly to the parts, so controlling one-degree of freedom of one-part relative to another.

The size of a gap between two parts is calculated using statistical methods, to account for the part's manufacturing tolerances, and to accommodate any additional

materials such as paint and adhesive. This significantly reduces no-gap or over-sized gap events.

Finally, Finite Element Modelling (FEM) was used to calculate an optimum pocket roughing sequence for both single-sided and double-sided metallic parts from a billet, minimising distortion due to residual stresses, and enabling first-articles to be manufactured first-time; leading to a significant cost-saving and a reduction to the overall make-span, particularly for one-offs.

1.6.2 New Research Questions

This research has highlighted a number of new areas to be researched. The use of the Measurement Assisted Determinate Assembly (MADA) method, fitting between DA/ICY and one-way methods, to drill a part to fit into an existing assembly based upon measurement data collected in the assembly-hall. There are a number of threads to this research such as, methods of collecting and processing the data, scheduling the drilling with the use of sub-contractors or other internal line of business, and the impact on the make-span. This would complete a suite of three methods for drilling parts to be assembled using MAA.

A further area to be researched is how to use the measurement data to create an As-Made Digital Twin that can be virtually assembled, to highlight potential quality issues in advance, and to provide confidence in the assembly process.

A final area to be researched is the extension of the part-to-part AM shimming described above to enable AM shim of the skin to structure joints, to achieve outer-mould line control.

1.6.3 Negative Results

The area where the results were not as expected or predicted was the shim layer thickness. The AM shim layers produced were not thin enough, nor accurate enough, to lay multiple layers within the sealant allowance.

1.6.4 Onward Use of This Research

This research has been the catalyst for BAE Systems to invest in its Factory of the Future, with the aim of demonstrating how automation can be used to assemble the next-generation of air vehicle.

1.6.5 Applicability to Other Sectors

The findings of this research might be of potential interest to sub-sectors of the aerospace sector such as the emerging air-taxi sector, and the automotive sector for the assembly of doors, bonnets and tail-gates.

2 The Business Need

This chapter explores the acquisition process used by the Ministry of Defence, and the Crown, for procuring defence equipment. The personal motivation has been the once in a life-time opportunity due to the infrequency of modern fast-jet projects which turn into production programme, and the chance to influence from the start rather than work to a set agenda.

Everything these days has to be affordable, the word is over-used, diminishing any impact, but understanding affordability and the wider implications, as well as the how and why has been very enlightening.

Affordability was identified as the business need for this research, and while definitions exist in other sectors such as social housing for example, it has been defined in an aerospace and defence industry context as:

‘... the degree to which the Whole Life Cycle Cost (WLCC) of an individual project or program is in consonance with the long range investment capability and evolving customer requirement.’

The definition divides into four sections; ‘the whole life cycle’, ‘in consonance’, ‘long range investment’, and ‘evolving customer requirement’.

The ‘whole life cycle’ in the context of UK defence projects is governed by CADMID (Concept, Assessment, Demonstration, Manufacture, In-Service & Disposal); a six phase acquisition lifecycle that is in agreement or compatible with the customer’s (UK MoD and the Crown) funding through the defence budget, and as defined by the government in its Strategic Defence & Securities Review (SDSR).

This chapter will discuss the defence budget, the impact of uncertainty, the SDSR, affordability factors, cost of an airframe, Tempest, and CADMID.

2.1 Defence Budget

The UK spending on defence has decreased from 6 percent of GDP at the height of the cold war in 1960, to 4 percent when the Berlin Wall collapsed in 1990, to 2

percent by 2000, where it has remained to the present day. While tied to the economic performance of the country, it is largely viewed as only being of political and symbolic importance.

Until 1983 there was no requirement for the UK MoD (UK Ministry of Defence) to inform Parliament of its spending. That changed with the purchase of the Polaris system (the UK's first submarine-based nuclear deterrent), and the disclosure in the 9th report to the Public Accounts Committee - HC269 (Great et al., 1982), that successive UK governments had hidden the escalating cost until the overrun topped £1 billion and the secret inner-Cabinet spending approvals could not continue. The MoD was then instructed to submit an annual report on their major projects. The reports are scrutinised annually by the National Audit Office (NAO), but until 1993 the data they contained was classified as confidential, and the format hinders any meaningful analysis of cost overruns and time slippages (National Audit Office, 1994).

The reports were intended to advise Parliament of the progress and cost of the top 25 major defence equipment projects, however some facts and figures remained commercially sensitive and were provided in a separate memorandum. Typhoon Tranche 3 negotiations held between 2004 and 2009 are an example; the project and variation costs were suppressed. This makes assessing the cost of a project, in the context of this research the acquisition cost of Typhoon, difficult until the figures are released.

The first Equipment Plan produced in 2013 covered the period 2012 to 2022. It is an annual report which provides a view of the UK MoD's forecast expenditure plans for the next ten-years to meet the objectives set out in the National Security Strategy (HM Government, 2010). It is assessed annually by the NAO, and the latest plan (Ministry of Defence UK, 2018b) covering the period 2018 to 2028 was deemed unaffordable (National Audit Office, 2018: pp 4). The NAO identified potential a "black-hole" of between £4.9 and £20.0 billion, which means major projects will have to be reduced, delayed or cancelled.

The current plan does not include Tempest, a next fighter aircraft concept, but does include the up-grade of Typhoon to extend its life to 2040 when Tempest will replace it, and the purchase of the remaining JSF F-35s. It raises the question of

what the UK MoD can afford in the next decade, particularly as Tempest in-service date is 2035.

2.2 Impact of Uncertainty

The Royal United Services Institute (RUSI) identified that while delays and cost overruns to defence programmes have many causes, one cause universally recognised is the “conspiracy of optimism”, (Weston et al., 2007), which had been identified as an important factor in the initiation of many projects, (Moffat and Gardener, 2006). This behaviour, was validated using Game Theory – the Prisoner’s Dilemma, (Moffat et al., 2006), showing it was driven by “uncertainty”; which if high the rational strategy for both parties is to be unrealistic about project costs and risks. The Mega-projects paradox, while based on investigations in the transport domain, found that “more and bigger projects continue to be built despite a consistently poor performance (cost & delivery) record”, (Flyvbjerg et al., 2003). There is also evidence to suggest the promoters will proceed with these projects so long as they are not personally accountable, and that an element of delusion is necessary to get projects started.

In the context of this research, there is uncertainty as to what the next generation of fast-jet will be as both manned and unmanned air vehicles are currently proposed, as is the concept that the airframe is “designed for growth”.

2.3 Strategic Defence & Securities Review

The defence budget has been under pressure for more than a decade. In 2008 the Secretary for Defence asked Sir Bernard Gray to undertake a review and look at how to improve defence procurement, or Acquisition Reform as it is generally known, (Gray, 2009). One of the recommendations he made was to hold a Strategic Defence Review (SDR), he also looked at the facts behind headlines such as:

“How can it be that it takes 20 years to buy a ship, or aircraft, or tank?”

“Why does it always seem to cost at least twice what was thought?”, and

“Why does it never quite seem to do what it was supposed to do?”

Investigating the consequence of uncertainty and optimism he concluded defence programmes were on average delivered 81 percent late and 42 percent over budget; he also noted it was difficult to determine how much capability originally sought was delivered because there was plenty of evidence of de-scoping. Investigating the consequence of uncertainty and optimism, Gray concluded defence programmes were on average delivered 81 percent late and 42 percent over budget, (Gray, 2009); noting it was difficult to determine how much capability originally sought was delivered because there was plenty of evidence of de-scoping.

Gray also recommended the introduction of a Strategic Defence Review, which the Secretary of State for Defence at the time saw as an opportunity to “make a clean break from the military and political mind-set of the Cold-War”. The first SDSR in 2010 saw the cancellation of the Nimrod MRA4 project, which was over nine years late, had had technical difficulties, and was £798 million over budget, (Clarke, 2011).

This supported the argument that a conspiracy of optimism exists between the UK MoD and the defence industry; the initial estimates for cost and delivery were too low and too ambitious, as on average they cost more and are delivered late. This impacts the budget, creating the current “black-hole”, as identified in Section 2.1, pp 17.

2.4 Affordability Factors

Nine factors that affect the affordability of the whole aircraft programme were identified through interviews, (Bankole et al., 2009), see Figure 3, pp 21. A number of these factors (World Economic Climate, Political Situation, and Legislation) are driven by global issues and are unlikely to be directly influenced by the engineering objectives of this research. Those that can be are Requirements, Supply Chain, and Quality; which represents 35 percent.

When the customer changes the requirement extra effort is needed to redesign the system, increasing the life-cycle costs. With the increasing dependency on lower tier suppliers to help deliver products and services, it is a major challenge to ensure

continuity in the supply chain for the life of a contract, which may be as long as 50-years. The customer wants to ascertain that the solution delivered is high quality, so their view of affordability is influenced by their perception and interpretation of the quality within the project. These factors are discussed in greater detail by Bankole et al (Bankole et al., 2012) in their assessment of customer affordability.



Figure 3: Qualitative factors affecting Affordability (source: Bankole, 2009)

Typhoon is an example of changing requirements, originally designed as a fighter, the changing political situation in the late 1980's necessitated modification to a multi-role aircraft. The requirements for the next generation air vehicle will be derived from a consensus of expert opinions as to what the world will require 2035 and beyond, which is why one of the cornerstones of the approach applied in the Tempest project is upgradeability, its physical architecture is "designed for growth"; another is affordability including automated support options for in-service.

2.5 The Cost of Assembling an Airframe

This research has looked at assembling the airframe into which the systems, equipment, engines, etc. are installed.

It has been estimated, and it is an estimate as aerospace companies regard this information as proprietary and competition sensitive, that the airframe represents between 10 and 15 percent (Ferguson, 2018) of the total cost of a modern fighter, which for Typhoon with a unit cost of £72m would value it at between £7.2m and £10.8m.

In modern airframes, the parts delivered to the assembly halls already contain most of the material and labour costs for their fabrication, therefore the main cost in assembly will be the touch-labour that is used to load, drill, and fasten them together.

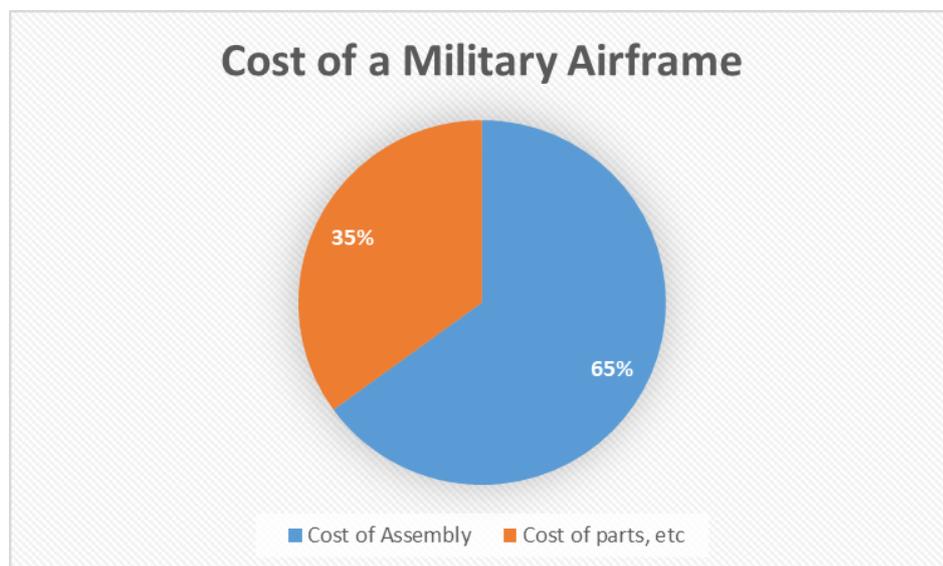


Figure 4: Cost of a Military Airframe

The cost of assembling a military airframe is approximately 65 percent of the cost of the airframe with the parts, details, and components accounting for approximately 35 percent, (Bullen, 2013), see Figure 4, pp 22. Touch labour hours are therefore the largest contributor to the cost of modern airframe production.

Other estimates, (Martin and Evans, 2000), indicated material plus fabrication, engineering, and assembly, represents approximately 50 percent of a “system”, and assembly related operations were estimated to account for over 40 percent (Bullen, 1999) of the total airframe manufacturing cost.

The labour costs for assembly and fabrication as a percentage of the airframe cost have further been estimated as 40 percent and 20 percent respectively, see Figure 5, pp 23.

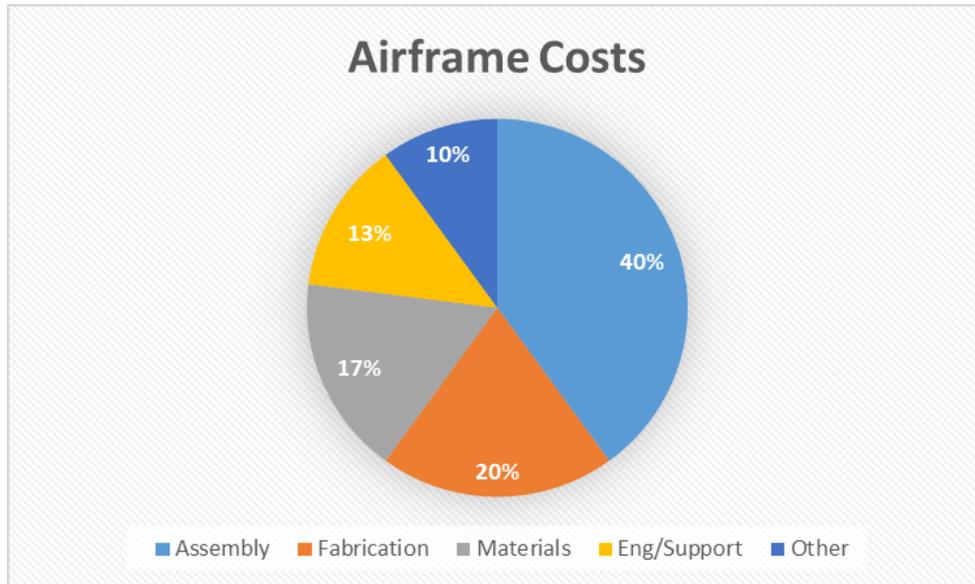


Figure 5: Airframe Costs

Assembly can be further divided into the four basic process; location, drilling/countersinking, fastening, and other including sealing, of which the actions of drilling/countersinking and part placement account for three quarters of the total labour.

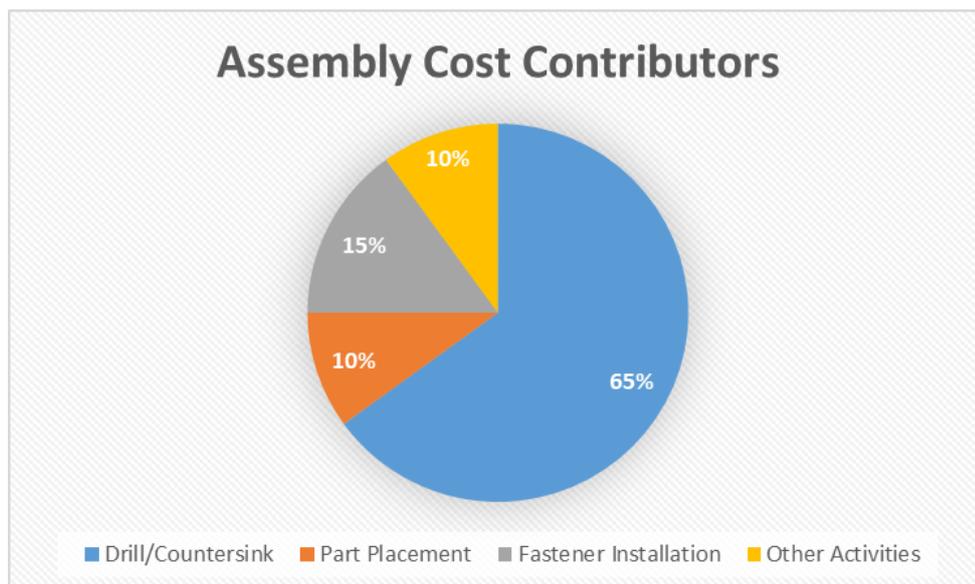


Figure 6: Assembly Cost Contributors

Drilling/countersinking is the largest cost at 65 percent, see Figure 6, pp 23.

Therefore this research can impact 75 percent of the touch labour cost of assembling an airframe, through new, novel, and innovative methods of locating the parts and drilling/countersinking the fastener holes.

In addition to the recurring costs the non-recurring or capital costs paid by the UK¹ have been estimated to be 9 percent (£1.8 billion) of the Development and Manufacturing phases' budget (£20.2 billion); this value was determined using figures available in the 2010 MoD Major Projects Report produced by NAO (National Audit Office, 2010: pp 191).

The approved cost of the demonstration and manufacturing phase was £16,671m and the forecast was £20,182m, an increase of £3,511m.

The development costs were originally approved at £3.2 billion, but with the change of role, the forecast is £6.7 billion; an increase of £3.5 billion, which is consistent with the increase in the demonstration and manufacturing phase.

The number of aircraft the UK is purchasing is 160, at £73.1m each, the production costs are:

$$= £73.1m \times 160 \text{ aircraft} = £11,696m \text{ (£11.7 billion)}$$

The demonstration and manufacturing phase is the sum of development, capital and production costs. Therefore, in billions:

$$£6.7 + \text{capital} + £11.7 = £20.2$$

$$\text{Capital} = £20.2 - (£6.7 + £11.7) = £1.8 \text{ billion.}$$

The cost of capital to the Typhoon project, in the UK, is £1.8 billion, or approximately 9 per cent of the budget.

2.6 Tempest – The Next Generation of Air Vehicle

At the beginning of this research the general view in the industry and Europe was the next generation of air vehicle would be an unmanned air vehicle (UAV), and be

¹ The UK ordered 232 a/c from a total of 620 a/c needed by the four partner nations. The total non-recurring cost to Eurofighter GmbH is estimated at £1.8bn *620/232, or £4.8bn.

part of an Anglo-French programme called Future Combat Air System (FCAS); this had built on over ten years of development which had culminated in the UK with Taranis, and Europe with nEUROn, see Figure 8, pp 26.

To support FCAS a partnership between the UK defence industry and its closest allies was announced in the 2015 SDSR, creating FCAS Technology Initiative (FCAS TI), valued at £2bn over 10-years. It also reaffirmed the UK would work with France to develop an Unmanned Combat Air System (UCAS), see Figure 7, pp 25.



Figure 7: UCAS Model (source: BAE Systems)

A subsequent joint governmental announcement in 2016 further reinforced the Anglo-French alliance with £1.54bn of funding to build a prototype of Future Combat Air System (FCAS), but within twelve months it was evident the project had stalled; based upon comments made by Dassault's chief executive while presenting their 2017 financial results.

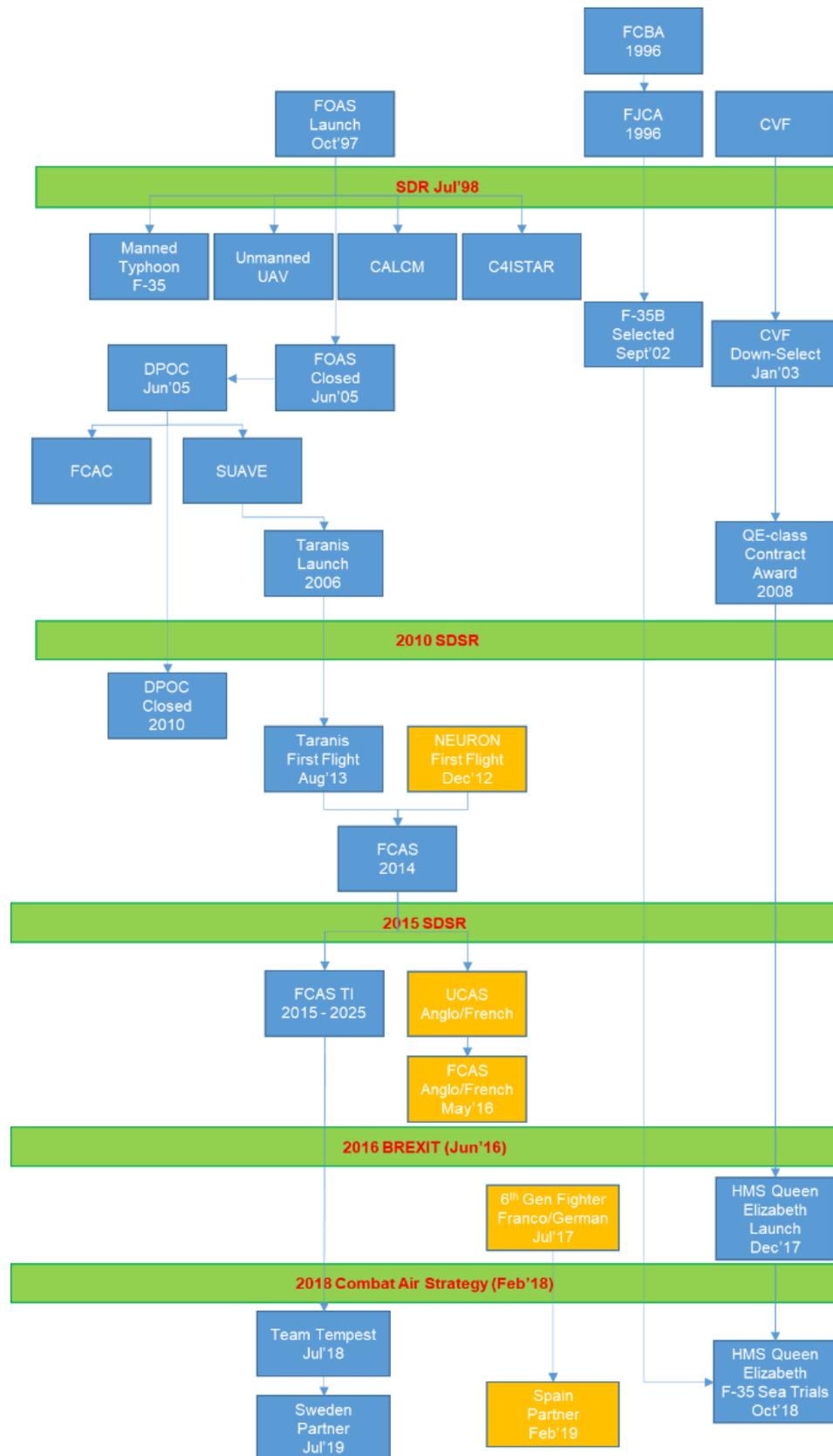


Figure 8: FOAS to Tempest (1997 to 2019)

Between these events, in June 2016, unexpectedly the UK voted to leave the European Union, possibly the biggest political event in Europe since the unification of Germany, 25-years before, which was a source of delay to the Typhoon programme, (Esitashvili, 2020).

Possibly in a show of greater European unity, a Franco-German 6th Generation Fighter was unveiled at the Paris Air Show in July 2017 as are placements for Rafale and Typhoon fighter jets by 2040; changing the focus of the whole industry from unmanned to manned. A common requirements document (CRD) was signed 10-months later, along with an announcement that Airbus would partner Dassault, aligning the French military manufacturer with the Franco-German-Spanish civil manufacturer and their Defence and Space division. In February 2019 a two-year joint concept study (JCS) started, and by June at the Paris Air Show a mock-up was available, see Figure 9, pp 27, and the Spanish had signed as a third partner nation.



Figure 9: Franco-German-Spanish Future Combat Air System sixth-gen fighter concept

The mock-up was introduced as the Next Generation Fighter (NGF) along the other elements of the FCAS/SCAF System of Systems, the Remote Carriers (RC) and an Air Combat Cloud (ACC). The aim is to have flying prototypes by 2026.

However, it was not just the Franco-German alliance who were proposing alternative air vehicles. At the Farnborough International Air Show in July 2018 three announcements were made but the way they were presented and reported had

everyone initially believing they were just one, called Project Tempest. In fact three closely linked announcements were made, firstly Team Tempest was unveiled (Hoyle, 2018). Comprising of BAE Systems (UK), Leonardo (Italian), MBDA (UK-French), Rolls-Royce (UK) and the RAF's Rapid Capability Office, it was the result of 2015 SDSR funding described earlier, and activities include between 50 and 60 demonstrations, covering aspects such as advanced sensors, propulsion and future cockpit design, all contained within FCAS TI, and will be followed by a more production-focused initiative (Stevenson, 2018).

Also announced was Tempest and the formation of a team to look at the combat air acquisition programme, effectively starting the process for the acquisition of a new aircraft.

Finally, the third element was the Combat Air Strategy, a framework for the government in which future decisions are going to be made.

While Italy (Kington, 2019) has suggested it might join the project at The Royal International Air Tattoo (RIAT) 2019 Sweden (Hoyle, 2019) did join, but Saab, the manufacturer of the Gripen will not join the Team Tempest industry grouping, rather they will work in cooperation, "to scope out joint development and acquisition programmes for both nations", Andrew says, (Hoyle, 2019)

Italy joined Tempest, signing a government-to-government at Defence and Security Equipment International (DSEI) 2019 (Stevenson, 2019), and elected to collaborate with British companies in the Team Tempest industrial partnership; allowing Leonardo Italy, Elettronica, Avio Aero, and MBDA Italy, to join with BAE Systems, Leonardo UK, Roll-Royce, MBDA UK, and the UK MoD Rapid Capabilities Office.

Further discussion on FCAS, FOAS and Tempest has been added in Appendix A, pp 159, and a similar narrative is available for Typhoon, (Kopp, 2000).

2.7 Defence Procurement Life Cycle Model

CADMID is the lifecycle model used by the UK MoD, and as discussed above, the announcement of Tempest triggered the formation of a team (an Integrated Product Team (IPT) formed by the Defence Procurement Agency) to develop the acquisition programme.

Acquisition is defined as the first four phases of CADMID, see Figure 10, pp 29. Details of the CADMID process and each phase are described in The Acquisition Handbook (Ministry of Defence UK, (2002)) and the National Archive of the Ministry of Defence's Acquisition Operating Framework (AOF), (Ministry of Defence UK, 2009).

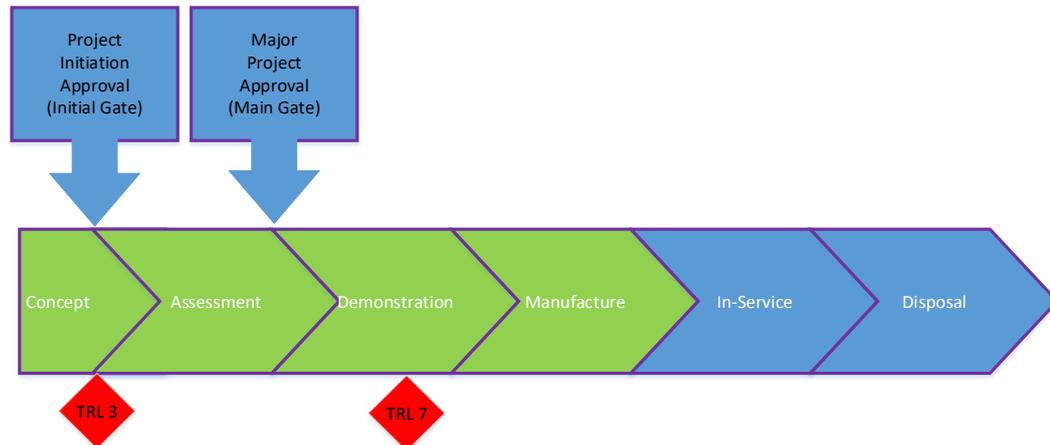


Figure 10: CADMID Acquisition Phases

The purpose has been understanding when to insert the technology and innovations developed as part of this research, and what level of capability in terms of technology readiness levels (TRL) it should be. The purpose has been to understand when to insert the technology and innovations developed as part of this research, and what level of capability in terms of technology readiness levels (TRL) they should be. TRLs were reported on by NAO for the first time in ten-years in 2012 (National Audit Office, 2013), and the key findings were:

- The National Audit Office (NAO) reported that TRLs were being investigated by the MoD in 2001 in an attempt to quantify risk before the Main Gate approval of Major Projects.
- TRLs became mandatory in 2002/2003, and were set at TRL 3 before the Initial Gate, and TRL 7 for the Main Gate.
- A review of ten projects determined that at the Main Gate the TRL was assessed to be between TRL 6 and TRL 8, and those below TRL 7 had a plan of action to achieve TRL 7 by the Critical Design Review (CDR).

- It was ten-years before there was clarity, and the annual NAO report stated that at the start of the Assessment phase the technology needs to be TRL3, and TRL 7 at the “point of the main investment decision”; this is likely to be when the first development aircraft is flown which on the Typhoon programme triggered the placement of the production contract.

The conclusion is the technology used to assemble first development aircraft needs to be at TRL 7, which has not necessarily been the case on past aircraft.

2.8 BAE Systems - Changes

BAE Systems plc, a global defence, aerospace and security company is the sponsor of this research. It employs approximately 82,500 people worldwide, and its products and services cover air, land and sea, as well as advanced electronics, security, information technology, and support services. In 2015 its earnings were \$25.3 billion.

For financial reporting purpose, it reports performance against five segments. In 2014, air activities were undertaken by Military Air & Information, part of the Platforms & Services (UK) segment, and its programmes included (BAE Systems plc, 2016: pp 38);

- Production of Typhoon combat and Hawk trainer air vehicles,
- F-35 Lightning II design and manufacture,
- Support and upgrades for Typhoon, Tornado and Hawk, and;
- Development of next-generation Unmanned Air Systems and defence information systems.

However, large organisations evolve, and there have been changes that impacted the projects associated with this research.

In July 2017 Dr Charles Woodburn took over from Ian King as CEO, and in October 2017 he announced a revised organisational structure, which took effect on 1 January 2018. It re-aligned the Group’s operations from five segments into four sectors: Air, Maritime, Land, and Applied Intelligence.

This research is now being undertaken for the Air sector, which accounts for 52 percent of sales, and is a combination of Military Aircraft & Information (MAI) from the Platform & Services (P&S) UK, and the whole of P&S International, which consisted of the Saudi Arabian, Australian and Oman operations, as well as the Group's interest in the MBDA joint venture.

The reason for the reorganisation is to accelerate the company's evolution into a more streamlined, de-layered organisation. Unfortunately, at the same time it was announced there would be a reduction in the workforce to align to current and expected future orders. The company had withdrawn from the TX competition, and there were no new orders for Typhoon.

Technology remains a key priority for the Group, and as of 1st January 2018 its first Chief Technology Officer (CTO) was announced to oversee technology development and investment efforts.

Nigel Whitehead, group managing director for P&S (UK) assumed the role of CTO for BAE Systems plc. In his new role he retained control of the Seed-corn funding budget which was used to fund the Integrated Autonomous Assembly Demonstrator (IAAD).

2.9 International Defence Sector

The defence sector is an international business, with the arms trade is a global industry, which is highly regulation. Business is conducted with governmental approval and through government-to-government contracts. For example, in the UK an open general export licence (OGEL) is required for development, production and sales of aircraft such as Typhoon; meaning there is a political element to the sector.

To illustrate how this sector is dominated by the North American and European States the current range of 4th and 5th generation fighters as well as the next of generation fighters have been mapped against the States participating in seventeen known programmes, see Figure 11, pp32 : Which State On Which Programme.

Regions		Programmes																	
		4 th / 5 th Generation Fighters								Next Generation Fighters									
Country / Programme		Typhoon	Gripen	Rafale	JSF F-35 (Partner)	JSF F-35 (Sales)	J-20	HAL AMCA	Mitsubishi X-2 Shinshin	Sukhoi Su-57	TAI TF-X	Tempest	FCAS - NGF	X-plane (NGAD)	F-X (F-3)	KF-X	Mikoyan MiG-41	J-XX program	AMCA mk2
Europe	UK*																		
	Germany																		
	Italy*																		
	Spain																		
	France																		
	Sweden																		
	Denmark*																		
	Norway*																		
	Netherlands*																		
	Turkey*																		
	Belgium**																		
	Poland**																		
	Israel**																		
	Russia																		
US	US*																		
	Canada*																		
Asia	Australia*																		
	China																		
	India																		
	Japan**																		
	Singapore**																		
	South Korea**																		

Legend	
Partner	Green
Ex. Partner	Red
Multiple Programmes	Purple

Figure 11: Which State On Which Programme

Data source is based on experience, press-coverage, news channels, and internet searches.

There are sixteen US or European states compared to six Asian. As an illustration of the political influence on the sector, Turkey were on the F-35 program (red square) until very recently, however they were removed by the US when they received the first parts of a Russian missile system. The uncertainty (purple squares) of the 6th generation market can be illustrated by Sweden signing a MoU with the UK for the FCAS programme, but not committing to the Tempest project; and the UK and US despite both being on other 6th generation projects looking to partner with Japan on their F-X (F3) programme.

2.9.1 Three Phases

Japan's decision to partner on their F-X (F3) programme, see Figure 11, pp 32, is an example of barriers states face to gain entry in the aerospace sector. These programmes are complex, requiring firms to develop significant project management and technological resources, and by extension it is suggested that states would adopt particular strategies to catch-up the leading nations. In the context of this research the existing literature on technology catch-up describes three phases, (McGuire and Islam, 2015).

Phase one is exposure to the technology by using foreign direct investment (FDI) to expose the indigenous workforce to foreign-owned technologies. The particular technology is implemented, usually as part of global supply-chain.

Phase two is when the firms understand the technology, not just the codified knowledge but the associated tacit knowledge too, and the third phase is when the firms are in possession of the technical expertise, embodied in scientists, engineers, etc., to be able to manipulate the technology to either create incremental or significant improvements.

2.9.2 Barriers

Barriers to entry are very high due to the capital commitment required to design and produce aircraft, whether for civil, in all its flavours, and military aircraft, (Niosi and Zhegu, 2005). Unlike other sectors, such as pharm and biotech, citations to patents and licensing are "useless" as a measure of the research being undertaken as aerospace companies tend not to publish scientific papers, or license technology, instead preferring to protect through secrecy rather than patents, (Niosi and Zhegu, 2005), which is an efficient method given the high capital barrier, (Vertesy and Szirmai, 2010), and limited access to it.

A mechanism used by states to gain entry is through the use of an off-set policy. Along with the contract to purchase a product, there is also a requirement that a percentage of work is done in country. As an example, Belgium recently announced it will be purchasing thirty-four CTOL variants of JSF F-35, rather than Eurofighter Typhoon, to replace its ageing Lockheed Martin / General Dynamics F-16. As part of this deal Lockheed Martin (airframe, and prime) and Pratt and Whitney (engine) identified industrial opportunities in technologies, and Research and Development,

across Belgium's three regions; In the area of additive manufacture, and relevant to this research, two of many organisations identified are KU Leuven (see Section 6.7 International Placement at KU Leuven, Belgium, pp 123) and 3D Systems.

In addition, companies within Belgium will be identified, by the Belgian government to manufacture metallic and composite parts, then assemble them into a major unit. The work will come from the existing workload of one of the three main partners, and require the transfer of data – codified knowledge. This will enable the Belgium aerospace industry to acquire or develop the associated technologies, which would form part of its overall aerospace strategy.

Countries seeking to develop the technology, will have previously under-taken off-set work or built under licence, before attempting to develop their own indigenous industry. An example of this is China; who has a history of working with Russia; many of the Chinese fighter being based upon MiG or Sukhoi designs. However, in the last twenty-years indigenous version of foreign aircraft have been produced, the Chengdu J-10 (Firebird), then in 2016 China announced "... we hope very much that Su-35 will be the last (combat) aircraft imports, ...", (Lei, (2017)), just after the Changdu J20, a 6th Generation Fighter, part of the J-XX program from the 1990's was announced. Associated with each aircraft company there is an institute; *601 Institute* is the Shenyang Aircraft Design Institute, and *611 Institute* is the Chengdu Aircraft Design Institute. As a result of greater state control over high-technology sectors, there is less separation between military-related research units, production and civilian enterprise, with the state-run universities and research institutes pursuing dual-use research agendas, (Treat and De Medeiros, 2014); something Boeing has adopted at the Black Diamond centre.

Finally, countries exploiting their knowledge on programmes, an example being Germany, who are part of the Typhoon consortium, and also partnering France and Spain on the FCAS – NGF programme.

2.10 Emerging Countries

China is an emerging manufacturer of civil and military aircraft to satisfy its own domestic demand. Since the early 1950's top officials have 'urged greater civil-military-industrial coordination and cooperation' (Cheung, 2013 : pp177). The

distinction civil and military is blurred, as discussed in Section 2.9.2, pp 33, on the international defence sector, as companies are producing both civil and military products, with each manufacturer having an *6XX Design Institute* associated with it, and there is greater state control (Treat and De Medeiros, 2014).

China initially undertook off-set work to build up its expertise and understanding of codified knowledge, before embarking on the manufacture of its own designs. However, as it is discovering not all knowledge is shared, and getting its civil aircraft certified is not as easy. Set to become, pre-COVID 19, the world's largest passenger aviation market by 2024, (Communication, (2017)), a situation that benefited sales by aerospace companies such as Boeing and Airbus. Historic disagreements over IP, particularly with the US, would normally have made aerospace a target in a trade-war, but the bilateral trade in aerospace products is huge and very one-sided in favour of the US, (Moreshead, (2018)). Comac, the Commercial Aircraft Corporation of China Ltd. is a state-owned aerospace manufacturer established in 2008, but its product range is currently years from entering the market and behind the competition, (Moreshead, (2018)), as demonstrated by its ARJ21 regional jet which made its maiden flight in 2008, but only received a production certificate from CAAC nine-years later in 2017, (Reuters Staff, (2017)); by comparison Bombardier or Boeing would expect to receive certification in two-years. Comac have collaboration agreements with Canadian owned Bombardier, Boeing, and Russia's United Aircraft Corporation (UAC), demonstrating the global nature of aerospace.

2.10.1 Made In China 2025

Abandoning the Soviet model of quantity over quality, China announced the "Made In China 2025" (MiC) initiative in 2015, with the aim of speeding up the development of its manufacturing sector. It is moving away from being seen as the "world's factory" with its lower labour costs and supply chain advantages, it is shifting from being a labour-intensive workshop into a technology-intensive powerhouse. It is no longer the lowest-cost labour market, with newly emerging south-east Asian countries such as Vietnam, Cambodia, and Laos providing competition, and it is not the strongest player in the high-tech arena, (Li, 2018).

Industrialised nations such as the US and Germany are all deploying digital technology to create new industrial environments, enabling a comparison with Industry 4.0 (I4.0) to be drawn, (Li, 2018). Both plans, MiC and I4.0, recognise the use of the Internet of Things (IoT), creating smart manufacturing systems both within and beyond the factory walls.

MiC prioritised ten industries including high-end numerical control machinery and automation, and aerospace and aviation equipment; which is evident in the available research, as discussed in Section 4.6.1, pp 61. Central is its semi-conductor industry, where advances may lead to breakthroughs in other areas. China is investing in aerospace research & development and human capital, due to the strict limitations on technology transfer from IJV, and the domestic initiatives are producing new research and engineers.

Publication of Chinese military research is limited, however a comparison between the US/European and China civil aerospace in measurement assisted assembly, enables the likely state of Chinese military research to be estimated, as the companies undertaking civil manufacture are military manufacturers too; and there is state direction.

China's commercial aircraft development will face major challenges in the coming decade. So far China has only assembled aircraft design and manufactured off-shore, with some local part production. Despite the ambition to deliver a commercial jet, it has not succeeded yet, (Eriksson, (2017)), key skills in programme management and technological resources are both difficult to acquire and costly to maintain, (Leten et al., 2007).

The Chinese military aviation industry is capable of producing fourth generation aircraft, equal to those operated by most advanced air forces, and now includes naval jets which can operate from aboard aircraft carriers, (Saunders and Wiseman, 2011).

To illustrate the size of a modern fast-jet programme, the South Korean KF-X, whose first test flight is scheduled for 2022, was developed with help from 16 universities, 11 laboratories, and over 500 suppliers, (Blog Before Flight Staff, (2020)).

Issues with engine design, avionics and systems integration, are likely to delay entry into service of China's fifth generation fast-jet (J-20) until at least 2020, which is 2 decades behind F-22, providing an indication that it is 15-20 years behind the US.

The conclusion is Made-in-China is focused by the state, while Industry 4.0 is general and driven by the market. Both have the same aim, to enable them to compete in the new industrial revolution.

2.11 North America

In contrast to China the North America aerospace sector is one of the largest and most powerful industries in the US, and it has a number of sub-sectors. While military aircraft and commercial airliners are the two main sub-sectors, others include unmanned aircraft systems (UAS) or drones, commercial space which designs, manufactures and launches advanced rockets and spacecraft, such as SpaceShipTwo by Virgin Galactic, and the emerging Urban Air Mobility (UAM) sub-sector.

The U.S. aerospace sector is considered the largest in the world, supplying both military and civil hardware to the rest of the world, for example the JSF F-35 programme, see Figure 11, pp 32, in Section 2.9 – International Defence Sector; originally it had eleven global partners, reduced to ten recently when Turkey were removed, and four export countries including Belgium. With great emphasis placed on R&D, approximately 25% of those employed in the sector are either engineers, scientists, or technicians. Key to this are organisations like the Defence Advanced Research Project Agency (DARPA) who are responsible for the development of emerging technologies for use by the military, and Air Force Research Laboratory (AFRL). These organisations and its fierce protection of military technology with the use of International Traffic in Arms Regulations (ITAR), a United States regulatory regime to restrict and control the export of defence and military related technologies, leads the US to be described as high-tech.

The US is working on its next generation of fighter jets, called the Next Generation Air Dominance (NGAD) program, considering radically altering its acquisition strategy. USAF could require industry to design, develop and produce a new fighter in five-years or less, (Insiina, (2019)). Making it possible for the Air Force to

rapidly develop and buy aircraft more frequently, challenging the acquisition paradigm; it could buy new aircraft every eight-years and replace them after sixteen-years, before 3,500 flight-hours are reached, when they need an extensive overhaul and modification to extend their service life.

Much of the program is classified, however the advanced manufacturing techniques which are critical to “building” NGAD were pioneered by the commercial sector, potentially “opening the door” for new prime contractors such as SpaceX to emerge and challenge the traditional primes of Boeing, Lockheed Martin and Northrop Grumman. The USAF has confirmed, using advanced manufacturing techniques, it has secretly designed, built and flown at least one prototype, (Insiina, (2020)), which shocked the defence community, who had last seen the first flight of an X-plane twenty-years previously, on the competition for the JSF contract.

There are similarities between this paradigm shift, and the emerging Chinese aerospace sector; companies developing technology that can be used in both commercial and defence sectors.

The competition to the US on a global scale is still seen as China and Russia, (Roper, 2020). This alternative acquisition strategy may be a consideration to a “cash-strapped” UK government, and threaten the Tempest programme.

2.12 Conclusions

Affordability was identified as the business need or driver behind this project, as the requirement for an affordable aircraft is evident from the assessment the NAO made in 2018 of the defence budget; it faces a “black-hole” of between £4.9 and £20 billion over the next 10-years. This is the legacy of decades of poor financial control by the MoD, which has seen past projects on average being delivered 81 percent late and 42 percent over budget, due to endemic “optimism” on the part of both the customer and the supplier.

While the budget deficit will impact current projects, with some being reduced, delayed or cancelled, the MoD is locked into a cycle of managing its annual budget to address the urgent affordability pressures at the expense of longer term strategic

planning, and is introducing new commitments without fully understanding the impact on affordability. This is leading to higher costs and reduced capabilities.

As a company BAE, and the industry, can only influence 35 percent of the factors affecting affordability, the others are either out of their control or simply unknown.

The cost of Typhoon's airframe has been estimated at between £7.2 and £10.8 million per aircraft, and 75 percent of the recurring work or labour content needed to assemble it can be impacted by this research. In addition the UK's contribution to the non-recurring costs, which are mostly incurred during the launch of manufacturing, is estimated at £1.8 billion and can be impacted too.

The next generation of air vehicle has been unveiled. Called Tempest it is part of a System of System (SoS), capable of being manned and optionally unmanned. It has cornerstones of being upgradable and affordable, using advanced digital processes during its manufacture and having automated support options when it is in-service. The setting up of the Acquisition IPT confirmed the CADMID process had started, and that in-turn set the TRLs that this research must achieve by certain milestones. The Concept Phase will continue until December 2020 (Mordaunt, 2019), when the preferred acquisition route and concept to be taken forward into the Assessment Phase will be selected. Therefore the technologies this research proposes need to be at TRL3 by December 2020.

Tempest, a partnership between UK, Italy and Sweden, is currently competing with the Franco-German-Spanish FCAS/SCFA SoS; both are very similar in almost every aspect of their design and timescales, but currently Europe is divided on a number of fronts, so an immediate alignment is unlikely, and neither project, particularly Tempest, has any non-European participants yet.

The greatest opportunity to embed the technologies and methodologies proposed by this research in the Tempest programme is through the FCAS TI funding route and Team Tempest, which is aiming to mature the technologies needed by future combat air systems.

The defence sector is an international business, but the current generation of fast-jets is dominated by the North American and European States. There are barriers to

creating and developing an indigenous aerospace industry, and they require government support typically last many decades to be overcome.

China is an emerging state, supported by its Made In China 2025 initiative, it is moving away from understanding the technology to having the technical expertise embodied in its scientists, engineers, and project management to significantly improve it.

Understanding Chinese fast-jet research, particularly in the field of automated assembly, is difficult due to the limited publications, however by comparing US/European and Chinese civil aerospace research, the condition of Chinese military aerospace research can be surmised; principally because Chinese aerospace companies undertaking both civil and military design and manufacture with state direction.

From the civil research reviewed, see Section 4.6.1, pp 61, there is evidence that high-end numerical control machinery and automation, two of the ten prioritised industries in MiC, are being used to assemble civil jets; the same technologies and approaches are being used in Europe. With China investing in aerospace research and development and human capital, and its stated hope that the Su-35 will be the last (combat) aircraft it imports; it can be assumed it will be investing in automation for military jets, and per US and European states.

The US, the largest supplier of both military and civil aerospace hardware to the rest of the world, is looking at its next program and considering radically altering its acquisition strategy by asking industry to design, develop and produce a new aircraft in five-years, and with reduced life (less than 3500 hrs), the Air Force will buy more frequently. This paradigm shift in acquisition would benefit from the agnostic, rate-invariant, automated assembly methodology that this research is proposing.

3 Current Best Practices

This chapter briefly describes current best-practices as used on the Typhoon and JSF-F35 programmes to manufacture and assemble the sections of the airframe BAE are contracted to build. The sections of airframe, termed “Major Units”, are fully equipped and shipped to final assembly lines in the UK, Europe, and America.

The motivation, particularly to document the use of machine tools on the assembly shop-floor, stems from the involvement in their introduction and the expansion of their roll. Therefore providing a unique perspective due to an in-depth knowledge, some of which has not been documented before, so it is time too.

3.1 State-of-the-Art on Current Programmes

If Tempest had to be manufactured and assembled on today’s shop-floor, it would still be done using techniques, methods, and processes developed during the 1990s for Typhoon and the 2000s for JSF F-35. The sub-structure parts would be machined from aluminium and titanium billets, and the skin would be manufactured from carbon-fibre using hand laid techniques.

The airframe would be assembled in a traditional welded steel fixture using the four craft-based processes of locating, drilling, fastening, and sealing. To achieve the aerodynamic and interchangeability tolerances sought high accuracy, temperature controlled machine tools would be employed to fettle sacrificial materials and drill skin and sub-structure fastener holes.

3.2 Assembly Fixtures

The assembly fixture has changed little since it was introduced in the 1930’s, and the issues with it are well documented, (Kihlman, 2001), (Martin et al., 2010), (Muelaner et al., 2011b). BAE has invested in alternative fixturing solutions but generally with only moderate success. Reconfigurable modular tooling systems have been developed and patented by both BAE and SAAB aerospace companies, (Kihlman and Engström, 2002), (Kihlman et al., 2004), (Scott et al., 2004), working in partnership with universities such as Nottingham, Cranfield, and Linköpings, then

commercialising the systems through SMEs, such as Boldman in the UK and BoxJoint in Sweden.

The tooling is designed in a CAD system directly from the airframe geometry using custom add-ons. The locators, or pick-ups, are assembled from standard parts such as tubes and clamps, see Figure 12, pp 42, and set using a laser tracker; a standard piece of equipment used in most aerospace companies to set traditional welded steel fixtures.

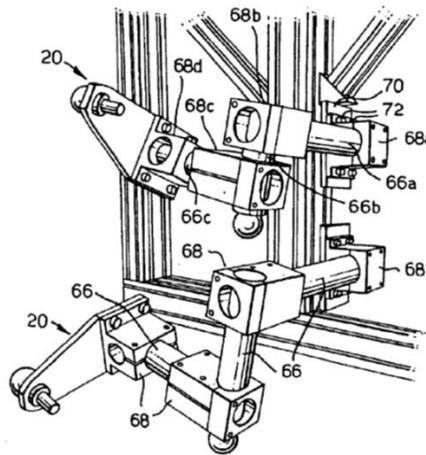


Figure 12: Patented Modular Fixtures (source: US Patent Office)

While these tooling systems have benefits such as shorter lead-times and a quicker response to change, particularly for the manufacture one-offs, prototypes, and in the early phases of production, they have drawbacks. They lack the robustness of welded fixtures so require more frequent checking/setting, taking them out of production, and effecting the Overall Equipment Effectiveness (OOE) measure. When used in a machine-tool the coolant can ingress into the tubes and extrusion, which builds up over time, and is a health and safety concern.

On JSF F-35 the system was used for the 23 development aircraft in SDD and at the start of initial low-rate production (LRIP) but it was not robust and led to quality issues; so when production shifted from cellular manufacture to a pulse-line the modular tooling was exchanged for traditional welded fixtures.

While SAAB have used flexible tooling on the one-off development aircraft, NEURON (Kihlman and Engstrom, 2010), and spin-off companies such as DELFOi

(Helgossan et al., 2010) and ProdTex (Erdem et al., 2016a) have continued to develop the concept of flexible, reconfigurable tooling, BAE have largely discontinued its use except where it is embedded in the production process such as on the assembly of Typhoon's fin at Samlesbury, see Figure 13, pp 43.



Figure 13: Eurofighter Typhoon Fin in a Modular Fixture (source: BAE Systems)

The airframe would be assembled predominately using the four craft-based skills, by skilled operatives who are referred to as fitters due to the fact that they “fit” the parts together. While the parts are machined to a high accuracy, the fact that they are thin and very flexible means the fitters have some latitude, such as “light hand pressure” which makes every product unique.

3.3 Machine Tools

Very accurate Dörries Scharmann Technologie (DST) flexible overhead gantry (FOG) machine tools are required to produce features such as holes and landings, as well as the edge profiles on the carbon skins for the JSF F-35 programme. They were introduced on the Typhoon programme, and known as DST ICY machines after the traditional method employed on the Tornado programme, known as cross-matched tooling, had failed to create interchangeable parts. The FOG machines were an improvement of the ICY column machines. This meant spares were supplied in a partially finished condition, and needed fitting; decreasing the

availability of the aircraft and increasing the time it is on the ground (Aircraft on the Ground - AOG). Interchangeability was a contractual obligation for Typhoon, (Anon, 2000), and had to be achieved on the first production aircraft, (Fowler, 1997).

The accurate machine tool, known as ICY machines on the Typhoon programme, and PMMs on the JSF programme, have evolved as the product requirements have tightened, and were affordable due to the volume (3500 aircraft) and rate (1 per day). There is also the additional support infrastructure required such as wash and dry stations to remove all oils and swarf from the products, and cranes/man-movers or pulse-lines necessary to move fixtures between the different cells. Gradually over the last three decades machine tools within BAE Systems have gone from being 3-axis and used for detail manufacture, to being very accurate 5-axis and an integral part of the manufacturing process, in both detail manufacture and assembly, with no manual alternative.

Currently they are used for:

- Stack-drilling (assembly)
- ICY drilling and Edge of Part (EOP) trimming (details)
- ICY drilling (assembly)
- Machining Hysol™ (assembly)
- Machining sacrificial carbon (details)
- Machining sacrificial carbon and glass-fibre packers (assembly)
- Independent drilling (detail and assembly)

The critical driver for this development of machine tools was achieving interchangeability (ICY) of panels, covers, and doors. Historically it was achieved using hard-tooling, but this approach was flawed, it used “red-line” master tools and copies which are not accurate enough. ICY was not achieved on 1000 Tornado aircraft; spares were supplied to the RAF bases with surplus material on them and manually fettled to it. The spares were metallic parts, on Typhoon they would be carbon, which is much harder to fettle manually.

ICY became a contractual obligation (Anon, 2000), and had to be achieved on the first production aircraft (Fowler, 1997). A specification issued by BAe to machine

tool suppliers in 1993 for the production phase of Eurofighter Typhoon, asked for previously unheard-of accuracy expressed in volumetric terms; most machine tool makers at that time were accustomed to thinking of errors, and quoting accuracy, in linear terms (Fowler, 1998).

Conceptual design studies by DST (a machine tools manufacturer, based in the former East Germany) led to a totally new configuration of machine tool. It was hoped that through the integrity of the machine and its measurement system, and careful calibration in a temperature controlled environment, the accuracy demanded would be achieved. A machine was built and initial trials achieved a volumetric accuracy of 200 μm , which was very good for a machine of that size, as similar sized machines would typically only achieve double that figure. Working with the Engineering Control and Machine Performance group at the University of Huddersfield, the most significant errors were determined and attempts were made by DST to reduce them by modifying the design. While the accuracy improved, it could not be guaranteed over the expected 15 year life of the machine.

The sources of the errors were repeatable, so a partnership between Huddersfield, DST and BAe was formed, and a 3-axis volumetric compensation system (VCS) was applied, (Ford, 2003). It achieved a volumetric accuracy expressed as a spherical tolerance of 72 μm in a 5m x 3m x 2.5m volume.

The initial agreement allowed DST to offer it to other companies needing ultra-high accuracy but not to competitors of BAe (Fowler, 1998). These machines were however an integral part of the manufacturing process that helped win the F-35 contract, and the partners would have access to this capability. In 2010, VCS was added to the Siemens' 840D controller².

While VCS brought the machine into the target range, there was a belief it could be improved further. Between 1997 and 2002, University of Huddersfield's Ultra Precision Engineering Centre, DST and BAe had a partnership agreement to develop a 5-axis geometric compensation method called KMS – Kinematic Measurement System, (Postlethwaite and Ford, 1999).

² [Siemens \(2010\): *Sales and delivery Compensation in Space VCS*](#)

These complex machine tools are very expensive, requiring temperature and sophisticated electronic control to achieve the accuracy demanded. Going forward it is recognised that this approach is not affordable, and the introduction of Automated (Robotic) Countersinking, see Figure 14, pp 46, has shown there are potential viable alternative methods that could address the first engineering objective, i.e., to reduce or eliminate the use of machine tools in airframe assembly.



Figure 14: Automated Countersinking (source: BAE Systems)

3.4 Conclusions

A paradigm shift in thinking is needed. The engineering objective is to find methods of assembling an airframe without the use of the traditional steel fixture and very expensive high accuracy machine tools, starting with a review of new ideas that are in the literature, which are covered in the next chapter.

4 Current State of the Art in Airframe Assembly

This chapter is a study of the current state of the art in airframe assembly in general and an investigation into the technologies used to determine if they might be applicable and transferable to fast-jets. A critical appraisal of the literature accounts for the differences in production requirements and business context which will affect their applicability.

The personal motivation was knowledge that relevant research had been undertaken, particularly in the UK, but there had not previously been the opportunity to appraise it specifically from a fast-jet perspective.

4.1 Introduction

This research sought to understand how automation could be applied to military aircraft airframe assembly.

There was a presumption, within the company, that automation either implied or meant the use of industrial robots, as they are considered an essential component of it, and they can be re-programmed, re-configured, and re-used, to provide the flexibility that the BAE sought, in its Smart Factory (Caggiano and Teti, 2018).

There are however a couple of significant differences between the applications that industrial robots typical undertake in manufacturing industry and those that they would be expected to do in an aerospace manufacturing environment; in general robots are known for their repeatability not their accuracy. Typical manufacturing applications rely on their repeatability and the programs are short, under three minutes duration, while aerospace needs accuracy, potentially over many hours.

Making industrial robots accurate has been the subject of both academia and industry research for more than two decades, with a number of solutions available. These solutions typically involve measurement using external metrology. Therefore using measurement or metrology to assist robotic assembly was the focus area of the literature review.

4.1.1 Submission no. 3B – Literature Review

Unpublished Submission no. 3B, (Carberry, (2016)), was the initial literature review, and the key findings were:

- The concept of Measurement Assisted Assembly (MAA) would be applicable to the automated assembly of the next generation of air vehicle.
- The processes of MADA and MARA, and the technologies of predictive processes, assemble-measure-move, and closed-loop control that support MAA could be physically used in the assembly process.
- Previous studies have examined the aerodynamic problems and so focused on the relationship between the skin and structure.
- The technology used to join sections of a fuselage together on a final assembly line can be transferred to assembly of the section or major-units.
- BAE has tended to focus on the physical world instantiation rather than the virtual world, so a holistic approach needs to be considered, involving the whole digital world; model-based definition, model-based enterprise, Industry 4.0, and digital-twins.

4.2 Key Sources of Information

The UK is at the forefront of aerospace research with a number of universities (Bath, Cranfield, and Nottingham), government-industry partnerships (Aerospace Growth Partnership – AGP, Defence Growth Partnership), supported by funding from government sources such as Department for Business, Energy & Industrial Strategy (BEIS), Innovate UK and the Aerospace Technology Institute (ATI), as well as the EPSRC for basic research, and through the EU, European funding such as Framework 7 and Horizon 2020. The University of Bath was the metrology hub for Airbus UK, and therefore has an understanding of the issues faced in general by the aerospace sector, more specifically by a civil manufacturer, and in particular related to wings. To support this field of investigation they set up the Laboratory for Integrated Metrology Applications (LIMA).

An initial literature search highlighted a concept called Measurement Assisted Assembly (MAA) proposed by researchers at LIMA and supported by Airbus UK. It listed the research priorities for MAA and a road-map to achieve them.

The issues identified for large scale assemblies are that the combination of demanding interface tolerances and flexible components prevents interchangeability, so manufacturers resort to fettling and shimming of parts, and stack drilling on assembly. The assembly tooling that is used is expensive to manufacture, has long lead times and little ability to accommodate product variability and design change, and while significant progress has been made to automate drilling the current production solutions rely on costly and inflexible gantry based machines.

These issues are very similar to those the next generation of air vehicle would face if current thinking was applied.

A specific source of information used in determining the current state of the art, which was previously list in Section 1.3 Methodology – Research Approach, pp 7, was the Society for Automotive Engineers (SAE). It is an outlet used by companies such as Electro Impact, Durr, and Brotje Automation to describe align system that are installed and used in industry. A search for automation employed on final assembly lines highlights systems to align and join sections of the aircraft. These systems handle large flexible assemblies, that need key features aligning, and achieve it by automating NC controlled manipulators and measurement systems; they have replaced what was a labour intensive manual process.

4.3 Early Examples of Fixtureless Assembly

Two early examples of using robots to assemble parts were the concepts of fixtureless assembly / manufacture (FLAM), (Hoska, 1988), and robotic fixtureless assembly (RFA), (Bone and Capson, 2003). The former recognised the time between introducing a product and its obsolescence was decreasing, and to remain competitive amongst other things there was a need to eliminate devices (tools, fixtures, and equipment) that are dedicated to a single product. FLAM was an approach which by Hoska's own admission was not achievable then. RFA represented an implementation of FLAM using 2D and 3D vision systems, which while having several limitations concluded that assembly accuracy would depend on the measurement accuracy.

4.4 Measurement Assisted Assembly

The University of Bath have proposed an overall framework called Measurement Assisted Assembly, see Figure 15, pp 51. It is supported by four technologies termed Predictive Processes, Assemble-Measure-Move, Active Tooling, and Closed-loop Control. These can be paired to achieve three processes, Measurement Assisted Determinate Assembly (MADA), Metrology Assisted Robot Automation (MARA), and Metrology Enhanced Tooling for Aerospace (META).

MADA and MARA are considered directly applicable to this research because they relate directly to drilling, robotics, and assembly, while only some elements of META are applicable such as the low-cost metrology network.

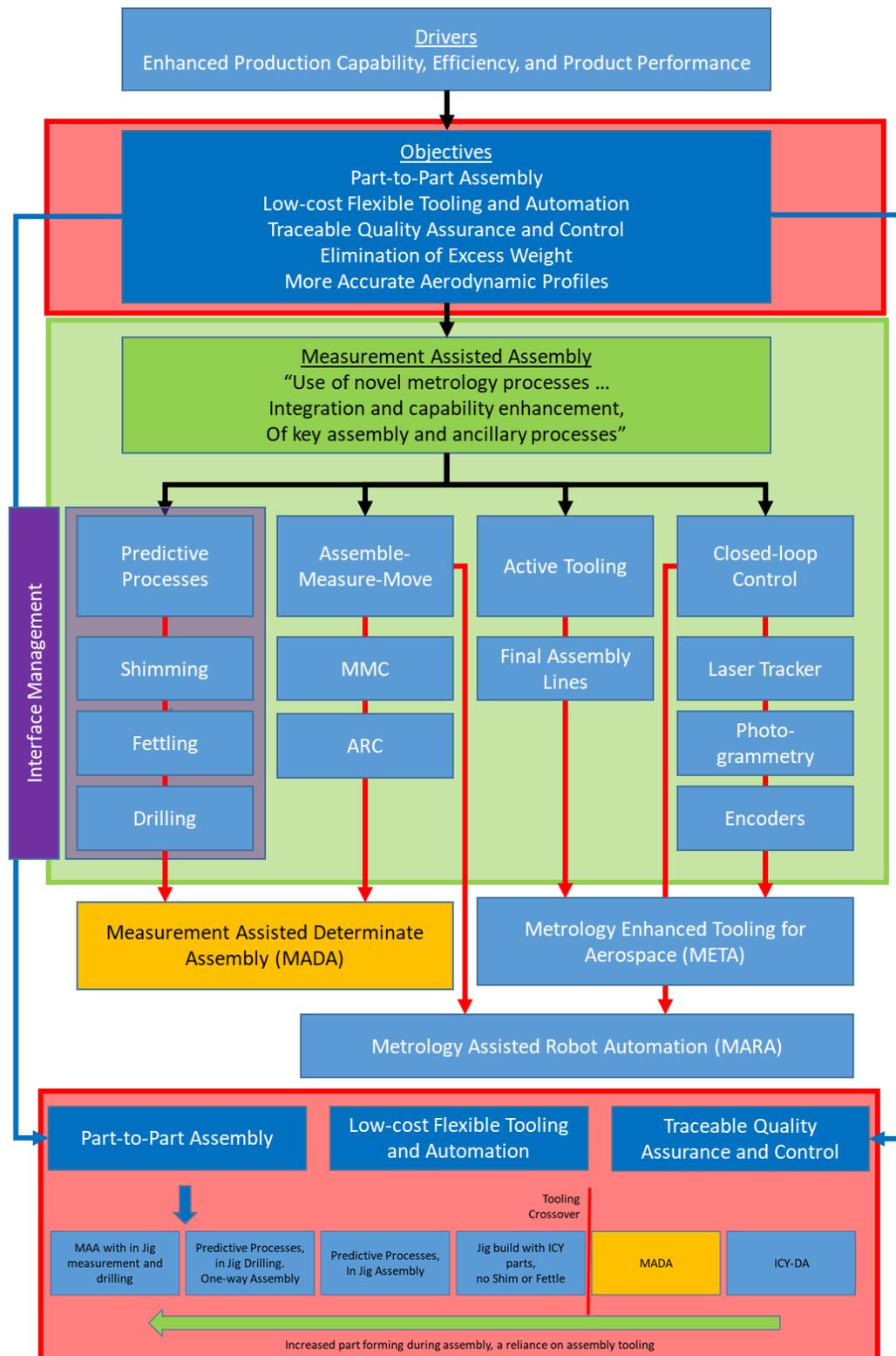


Figure 15: Measurement Assisted Assembly Framework

The basic assumption is that to achieve the tolerances demanded in assembly the parts are made, measured and then some form of adjustment carried out. The

adjustment can be to remove or add material to the part, or alter its location. The same process that is employed by the FALs.

MAA proposes three predictive process, namely fettling, shimming, and drilling, see Figure 15, pp 51. Current best practice involves fettling a non-structural material such as Hysol (a liquid shim), and this is primarily undertaken on the machine tools. Predictive shimming is only conducted on gaps over the maximum Hysol allowance, and predictive drilling is not currently undertaken on any production programme.

Finally, a series of part-to-part assembly paradigms were proposed, the first of which is determinate assembly with interchangeability, then MADA, and subsequent paradigms, which progressively require increasing levels of tooling, see Figure 15, pp 51.

4.5 Case Studies

The following case studies update to the unpublished literature review and summarise current research. The concept of Measurement Assisted Assembly was presented in 2007 (Kayani and Jamshidi, 2007), and built on a number of previous civil aircraft research and development projects, see Figure 16, pp 52.

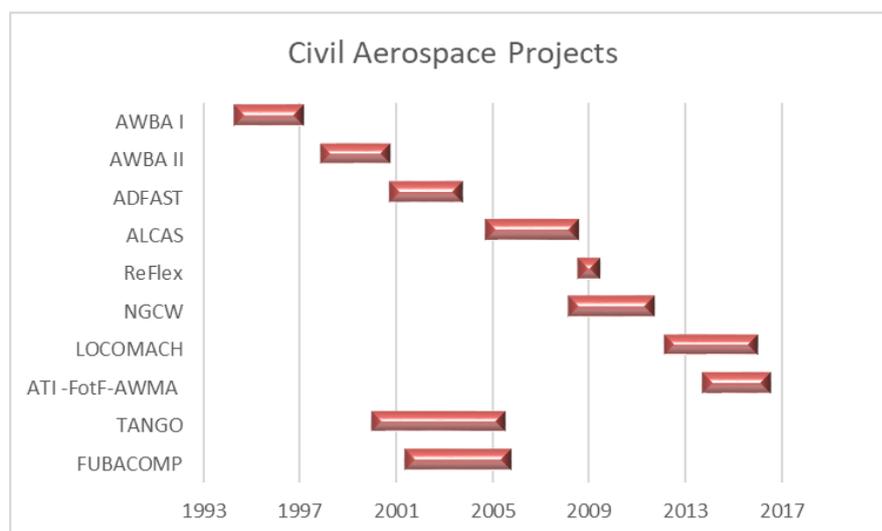


Figure 16: Civil Aircraft R&D Programmes Timeline

In the context of MAA the projects delivered the following technologies or methodologies.

4.5.1 Automation for Drilling, Fastening, Assembly, Systems integration and Tooling (ADFAST)

ADFAST demonstrated Affordable Reconfigurable Tooling (ART), a general name for a selection of elements that can be combined to create modular and reconfigurable fixtures, (Kihlman and Engström, 2002), (Kihlman and Loser, 2003), (Kihlman et al., 2004). It demonstrated that a standard industrial robot guided by a laser tracker, see Figure 17, pp 53, can position an adjustable pick-up to 50 μm , half the standard tolerance for assembly fixtures.

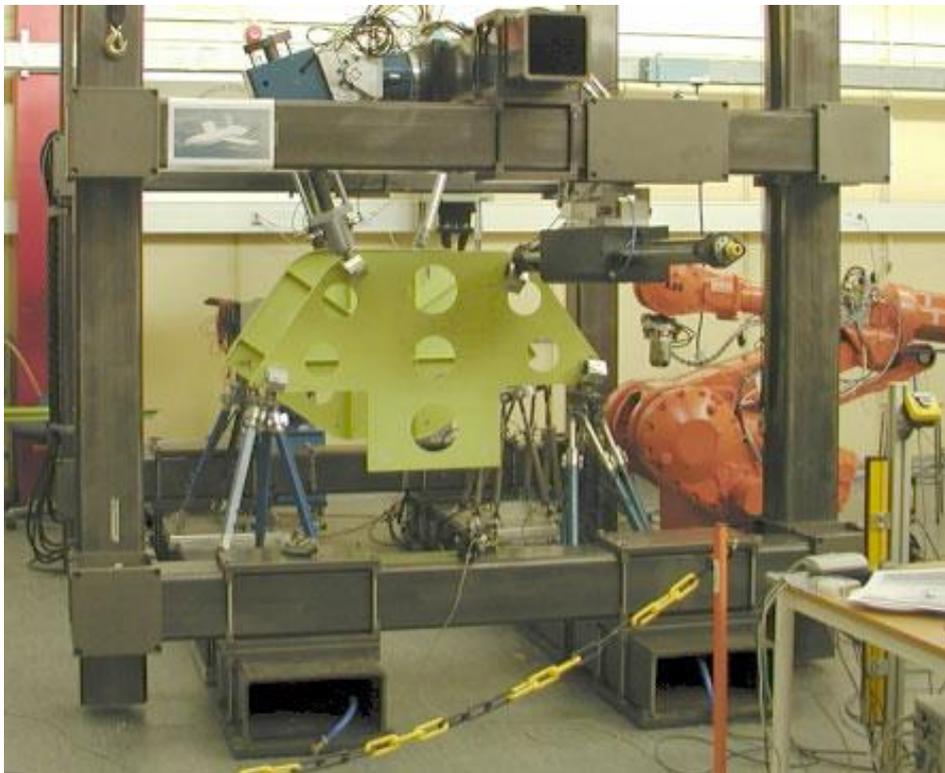


Figure 17: The ART Concept Tool (source: ADFAST)

This was an early demonstration of a variation Assemble-Measure-Move (AMM), one of the four enabling technologies for MAA. Critically, a substantial fixture is required and while it addresses the problems of coping with late-changes, and would be adjustable for product variants, operator access is restricted, the fixture is not readily reusable (the steel beams are cut to length), and there is limited automation. The location of the robot to set the pick-ups would not necessarily be the optimum

location for loading parts, then drilling and fastening joints, so may require relocation. It is however of a size to accommodate fast-jet parts such as those in a front-fuselage, and uses Stewart-platform type fixturing to support the assembly so releasing a robot should be explored further.

4.5.2 Reconfigurable Flexible Assembly Tooling (ReFlex)

The ReFlex project introduced the BoxJoint system, part of ART, (Millar and Kihlman, 2009). The robot and fixture were integrated via a seventh axis, enabling access to both-sides of the fixture, ideal for products that have operations undertaken on both sides, such as flaperons, doors, etc. The robot used a light-weight end-effector, also assembled from Box-Joint, demonstrating the versatility of the fixturing system. The creation of a light-weight end effector from a fixturing system, particularly with the design software behind it being automated, would speed up the creation of new systems.

4.5.3 Advanced Low-Cost Aircraft Structures (ALCAS)

ALCAS showed further development of ART, (Helgossan et al., 2010), using Mini-Flexapods; small 6 degree of freedom reconfigurable devices designed to eliminate shimming. Having a small working envelope ± 4 mm, (Jonsson, 2013), the shimming in this case was of the pick-ups and not between the parts. The Mini-Flexapods were not designed for frequent change, so a further development was the Semi-hyper Flexapod, (Jonsson, 2013), based on the Stewart-platform, making the fixture active as per Active Tooling, the third of the MAA technologies shown in Figure 15, pp 51. A motorised version of a Stewart-platform would negate the need for a robot to set it.

ALCAS also explored one of the three predictive processes, the fettling of rib feet, using a combination of adaptive robot control (ARC) and adaptive machining (Maropoulos et al., 2014). The ARC system normally has just one control point, for point operations such as drilling and fastening; in this case it had ten control points allowing a path to be followed. Fettling to better than 0.250mm makes it a viable alternative to machine tools that rout the edge-of-part. The negative is the level of checking that is required, a pass without a cutter, with a cutter, and off-setting due to inaccuracies in the overall system.

4.5.4 Low Cost Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS)

LOCOMACHS had not finished when the initial literature review was written, so was not discussed. It was a 33M € EU funded project under the 7th Framework Programme. A consortium, consisting of 31 partners from industry and academia, were tasked with addressing various aspects of aero-structure assembly, with special attention directed to the development of a new build philosophy with relevant enabling technologies. High-level objectives, while directed at achieving production rates of more than 50 aircraft/month, address areas of interest to this research, namely shimming, disassembly, and automation. Key findings of the project were:

- A 50 percent reduction in the recurring costs of non-value added shimming operations in structural joints,
- A 30 percent reduction in the recurring costs of non-value added dismantling operations, and
- An increased level of automation related to part joining operations.

The project focused on twelve breakthrough technologies (SAAB AKTIEBOLAG, 2019), four of which are directly relevant to this research:

- Additive manufacturing for shimming directly to composite parts (*no. 2*),
- Automation and humans in cooperative assembly operations (*no. 7*),
- Automated gaps and steps metrology solutions (*no. 9*),
- Integrated active flexible assembly tooling system (*no. 12*).

The following paragraphs summarise each technology and its impact on this research.

4.5.4.1 Deposition of Additive Manufacturing Shim (Breakthrough Technology no. 2)

An end effector for the direct deposition of ABS³ AM material onto the IML surface of a carbon skin was developed, (Antolin-Urbaneja et al., 2016). Using ANATOLEFLEX software, an assembly simulation was performed on component measurements to create an STL model of any gap. The model was then used by an

³ Acrylonitrile Butadiene Styrene used by 3D Fused Deposition Modelling (FDM), or Fused Filament Fabrication (FFF) printers.

ALM module to control an industrial robot and the end effector to deposit, using the hot-melt ABS process, shim to a positional accuracy of 50 μm and a minimum layer thickness of 90 μm .

This is directly applicable to this research in a number of ways. It overcomes the current lack of a shim model in the design by creating one; direct application negates the need to separately manufacture and attach the shims to the sub-structure parts; finally, the shims could be covered by a layer of glass-fibre, which is used to aid drilling and provide a galvanic barrier, to a) hold them in place, b) remove the need for an adhesive layer and clamps, and c) overcome the problem manufacturing curved shims.

The gaps identified in the AM process include, the need for alternative materials, determining the final accuracy of the end effector, and the placement of it on an accurate robot.

These gaps are similar to those identified during this research, and described later in this report in connection with manufacturing shims for the IAAD 1B assembly.

4.5.4.2 [An Automated Flexible Tooling Framework \(AFT\) \(Breakthrough Technology no. 12\)](#)

An automated flexible tooling (AFT) framework (Erdem et al., 2016b), and a Hexapod-based fixture (Erdem et al., 2016a) created a tooling technology that could facilitate the process requirements of automated wing-assembly using flexible tooling and intelligence support from a force sensor. The build philosophy was based on best-fit, where the aim was to manage thickness variation without the need for shimming, and use force to ensure face-to-face contact.

There is a similarity between this philosophy and that employed by some FALs, (Micale and Strand, 1996), (Rüscher and Mayländer, 2001), (Marguet and Ribere, 2003), namely the use of best-fit and sensory feedback. The design in this use-case was to move the variation to a lap-joint rather than a butt-joint, a common solution used in all metal aircraft. The variation is then absorbed in the edge-distance tolerance for the fastener holes.

4.5.4.3 Automation and Humans in Cooperative Assembly (Breakthrough Technology no. 7)

The two techniques, best-fit and force-feedback, were transferred to a collaborative robot (Kuka LWR), a robot with integral torque-control, to test safety solutions in an assembly cell, (Olsen et al., 2015). The research investigated robot-human collaboration tasks, an important aspect of BAE's manufacturing vision of working along-side robots without guarding. It defined and validated design and manufacturing rules for human-machine collaboration, in line with today's legislation (ISO/TS 15066 Human Machine Collaboration). As industrial supervisor of an EPSRC funded ICASE PhD at Cranfield University, similar work is being performed based on MircoSoft's Kinect and a UR5 robot, to understand the concept of trust.

4.5.4.4 Automated Gaps and Steps Metrology (Breakthrough Technology no.9)

Thermal stability, one of the main sources of variation in assembly, was addressed using light-weight carbon fibre reinforced plastic tubes coupled to zero-point clamps. Not new in their own right, the focus was on their use with flexible fixtures. The use of lightweight, thermally stable, end-effectors to hold and position the parts during the build of an assembly is a potential solution to the problem of the end-effector's mass being significantly greater than that of the part, and being the overriding factor when specifying a robot.

4.5.5 Metrology Assisted Robot Automation (MARA)

Robots are repeatable but not accurate, a fact that has been often highlighted, but the degree of inaccuracy is now more noticeable due to the increased use of CAD based offline programming tools. Historically, a basic robot was accurate to between 2 mm and 5 mm, but today most robot manufacturers offer a factory calibration option which improves the spatial accuracy to "better than" 1 mm, which is sufficient for most applications, (DeVlieg et al., 2002).

Greater accuracy can be achieved by constraining the motion to a single plane or operating within a reduced volume, but if the application requires greater accuracy without these restrictions then additional (external) control is required. This is necessary because the method that most robots use to determine their motion is to

measure the rotation of the axis motors not the motion of the joints, the opposite of machine tools.

A method to improve the accuracy is to integrate a metrology system (Kihlman and Loser, 2003), (Summers, 2005), (Van Duin et al., 2006), initial uses were limited to static processes, such as drilling and fastening, principally because of the delay or latency between the measurement and the correction, as well as the iterative nature of the move-measure-correct method.

For machining applications, such as those identified in Section 3.3 Machine Tools, pp 43, the latency plus a lack of stiffness means path following is inaccurate. Methods are being developed to improve the path following accuracy, (Lehmann et al., 2013), (Kingston, 2014). Using real-time, high-speed closed loop control, it is possible to correct a robot's path so that an accuracy of better than 0.2 mm is achieved at a speed of 50 mm/s. But at higher speeds "collisions" at corners indicated a loss of accuracy, and there was no load on the tool. This level of accuracy would enable the last of the four assembly processes, sealing, to be undertaken accurately, if the speed of robots can be matched to the flow-rate of the sealant.

The work has been further extended (Brown, 2019) to test real-time metrology guidance under load. For simple geometries in aluminium, such as a slot, the performance level was maintained, while for more complex geometry, such as a contour, it degraded. This indicated that for the more complex geometries, correcting a robot's path to a high level of accuracy remains a challenge due to the rigidity of the robot. The trial material was aluminium so the cutting forces, deflecting the robot, would be greater than those imparted if the material was carbon-fibre or Hysol™. Therefore, this method of controlling a robot has the potential to replace the need for machine tools when routing the edge of part on carbon parts, or predictive fettling of soft materials such as shim; alternatively non-contact processes such as water jet cutting may be used to rout the edge of part, as shown on IAAD 1B.

An alternative approach is to use a photogrammetry system such as the Nikon portable or K-series CMM. Using Adaptive Robot Control (ARC) software, the photogrammetry system can use the principle of move-measure-correct to re-

position a robot in 6 DoF, enabling it to be used for point-processes, such as positioning a part in space. Using a feature called Remember Last Offset (RLO) path-following can be improved (Holden et al., 2014), however the limitation is, that it's not real-time, and any changes to the path require the RLO to be up-dated by re-running the robot program a number of times; also it should be noted the program is run initially with no forces on the tool.

The most obvious limitation of these metrology systems is that they need line-of-sight to function, this has been addressed by adding external encoders to the joints (DeVlieg and Szallay, 2009).

4.5.6 Measurement Assisted Determinate Assembly (MADA)

Measurement Assisted Determinate Assembly (MADA) was proposed because there was a belief that the aerospace industry, and civil in particular, had not benefited from a reduction in production cost and cycle time that can result from greater assembly-efficiency, part-to-part interchangeability, and the use of flexible automation, (Muelaner and Maropoulos, 2010). It was proposed that through the application of measurement assisted processes and design for manufacture, parts could be produced with “relatively” slack tolerances and part-to-part assembly could still be achieved.

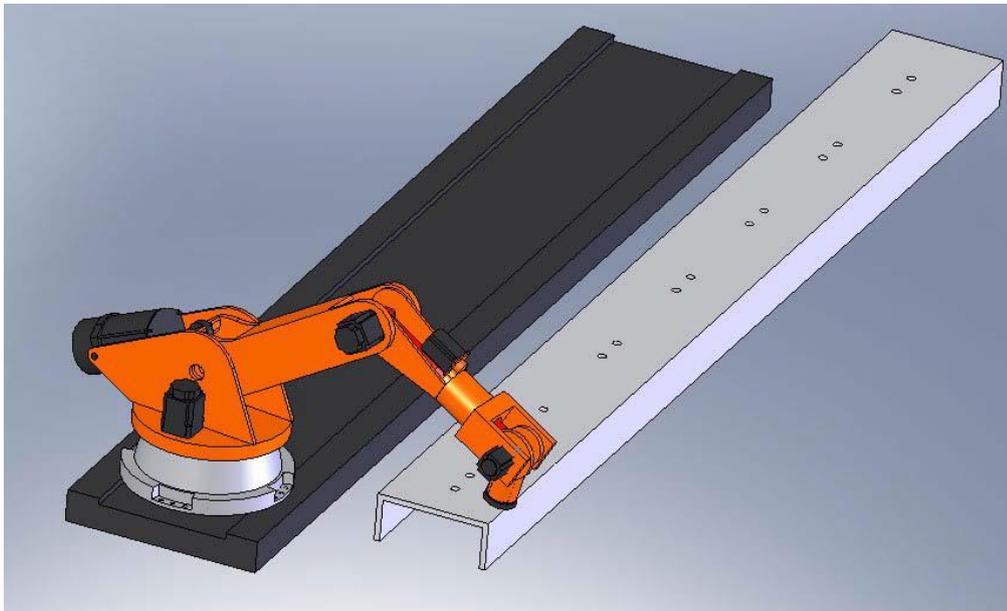


Figure 18: Industrial Robot on Linear Rail Drilling Spar to Low Accuracy (source: (Muelaner and Maropoulos, 2010))

The theoretical example provided was the drilling of hinge-line brackets along a spar, using an industrial robot on a linear rail, see Figure 18, pp 59. Using DfM the positional tolerance for the holes in the spar was increased to $\pm 500\mu\text{m}$, while the tolerances on the brackets remained unaltered. The proposal enabled an industrial robot on a linear rail to drill the spar, then the hole positions were measured, locally and globally. The data was then transferred to a machine tool to manufacture the brackets and drill the corresponding holes. The conclusions were, that while the drilling was achievable, measuring holes in the spar presented its own challenges. This may not be such a challenge for fast-jets, where the components are smaller, and would fit into a CMM.

Determinate Assembly was implemented on the leading edge sub-assemblies for wing manufacture, (Irving et al., 2014). Using a mathematical model it was shown that the current state of the assembly was “No-Go”, with an interference fit of almost 0.1mm. Adopting design for manufacture (DfM) the model was run with the diametric tolerance fixed, the positional tolerance changed. The conclusion was that while the cross-over point was 0.25mm, the additional cost of the resolution required from machine tool and the inspection processes meant 0.2mm was proposed and adopted. This highlighted the need to implement DfM principles early in the stages of aircraft design. This confirms early findings, (Muelaner and Maropoulos, 2010), that a conventional wing design was not suitable for MADA, and an alternative design was required from the perspective of tolerance management.

A variation of MADA was developed by ElectroImpact for Boeing (Landau, 2016). The system placed large structural parts, stringers, to an accuracy of $\pm 0.25\text{mm}$, using two industrial robots with closed-loop feedback controlled via an NC controller (Siemens 840D sl using the CNC SYMO (Siemens, 2020) compile mode).

ElectroImpact describes the system as a Dynamic Automated Positioning System, which is functionally similar to the FALs, (Rüscher and Mayländer, 2001), (Marguet and Ribere, 2003), (Maylaender and O'Rourke, 2009), the latest of which (Moreira et al., 2011), (Negroni et al., 2012), can be used to create an assembly more accurate than the components it is composed of by means of measuring and adjusting. Critically, the holes do not need high positional tolerance, thereby reducing manufacturing costs and increasing flexibility.

This indicates that multiple robots can now be controlled to an acceptable level of accuracy and not to distort a part or assembly as it is moved. Therefore a number of smaller robots could build an assembly, and then manipulate it in a coordinated manner, rather than use a single large robot.

4.5.7 Future Automated Aircraft Assembly Demonstrator (FA³D)

The assembly of IAAD will be described in more detail in the next chapter, but the system used at Nottingham University in the FA3D cell, comprising Kuka robots, Nikon K-CMM and MV331 Laser Radar, has been described in the context of Evolvable Assembly Systems, and specifically the MAA procedure (Drouot et al., 2018).

Evolvable Assembly Systems were inspired by examples of flexible and adaptive manufacturing systems that manufacturers adopted to meet changing customer demands and increased competition. It builds upon flexible manufacturing systems (FMS) (Browne et al., 1984), fractal architecture (Tirpak et al., 1992), holonic manufacturing systems (Van Brussel et al., 1998), and reconfigurable manufacturing systems (RMS), (Koren et al., 1999), and plug and produce (Antzoulatos et al., 2014).

4.6 International Defence Sector Research

The following three sub-sections review the research into Measurement Assisted Assembly (MAA), shimming of aero-structures, and adoption of additive manufacture in aerospace, in China and Europe.

4.6.1 Measurement Assisted Assembly (MMA) In Europe and Emerging States

Measurement assisted assembly was discussed earlier in this chapter, specifically, Section 4.4, pp 50, and a framework based upon the research priorities to enable a paradigm shift, (Maropoulos et al., 2014), was proposed.

A sub-section of an un-published literature review discussed automated alignment and marry-up systems used by manufacturers of both civil and military airframes. They are a useful sub-set of MAA to make a comparison between US/European and Chinese research.

In describing an automated alignment and marry-up system, the term Measurement Assisted Assembly (MMA) was first used, (Marguet and Ribere, 2003). The unpublished literature review covers development of these systems over the next decade, as various systems were installed world-wide. These systems are fundamental to the assembly of an airframe; without them it is almost impossible to achieve the aerodynamic shape required for efficient flight.

The US/European research is primarily reported and peer-reviewed via the SAE papers. As a consequence, current research mainly focuses on the process integration of measurement with assembly, (Zhehan et al., 2013), and ignores the uncertainty of the measured result and its influence on quality evaluation. A general observation is that, while investigating the same problem – alignment of parts using short-loop control, the Chinese research is more analytical, using more mathematics and optimisation techniques than the US/European research.

A recent European review of advances in large-scale metrology and future trends (Schmitt et al., 2016), highlighted short-term control-loops as the biggest challenge for both MAA and MADA. It is generally accepted that MAA is the best method for alignment of sections of a fuselage, wings and tail-plane; and while several metrology systems have been proposed, including MScMS (Franceschini et al., 2009), iGPS, and laser radar (LiDAR), laser trackers are the most popular due to their high level of accuracy and their existing use within airframe assembly, (Gameros et al., 2017).

Research in Germany at the Fraunhofer IFAM, has focused on mobile robot systems for machining of CFRP-parts, (Möller et al., 2017), on a continuous path. While the concept of a mobile robot is not new, (da Costa, 1996), this robot system has additional secondary encoder systems on each axis and is controlled by a Siemens 840D CNC controller, evolving the robot into a fully-featured machine tool, see Figure 19, pp 63. Using advanced calibration routines, and a combination of Denavit-Hartenberg and Hayati-Mirmirani methods for the Kinematic model (Schroer et al., 1997), bi-directional circular deviation $G(b)$ of $157\mu\text{m}$ was achieved.

Similar in arrangement are Electro-Impact's Robotic Applied Drilling System (RADS), which is on a rail, (DeVlieg and Szallay, 2009), and the Mobile Robot

Platform which has sled and additional vertical axis, (Gray et al., 2013); however these systems are designed for point operations rather than continuous-path operations.



Figure 19: Mobile Robotic System for machining application (source: Fraunhofer IFAM)

An alternative approach is the MARA system developed at the Manufacturing Technology Centre (MTC) near Coventry, (Kingston, 2014), and subsequently improved (Brown, 2019), where a laser tracker is part of a short-control loop. This method has the advantage of providing correction under load.

Chinese research presents an alternative approach for in-situ alignment and finish machining, using MAA. Identifying that there are three layouts of machine tools relative to the work-piece. The first is the work piece inside the machine tool, which is uneconomical (large machining volume, small surface area to be cut), the second the machine tool mounted on the work piece, typically used in circumferential drilling operations (fall-back for FAUB, see Belgium Placement, pp 125) and viewed as inaccurate. Finally, the work-piece and the machine tool are separate, allowing smaller machine tools to be used, (Lei and Zheng, 2017).

The assembly process is the most important part of aircraft manufacture, it is time consuming and impacts aerodynamic shape accuracy. Part-to-part assembly is usually infeasible on final assembly due to dimensional variations caused by pre-

assembly errors and temperature changes. It is uneconomical and sometimes impossible to achieve interchangeability of large-scale components, by improving machining or sub-assembly accuracy. The practical way is to preserve an allowance on the assembly interfaces, for finish machining (Lei et al., 2017). Before final assembly the allowance is removed, so the component fits within the tolerance allowed.

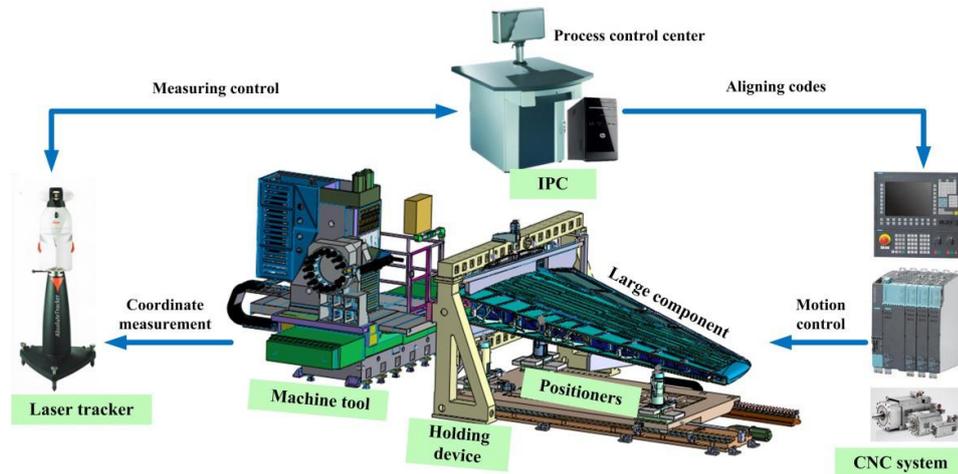


Figure 20: Framework of the finishing machining system for the large-scale components

(source: Per Lei et al, 2016)

Research (Lei et al., 2017) identifying informational loss between CAD/CAM and CNC using traditional G&M codes, proposes a closed-loop machining system based on an extended STEP-NC data model which includes alignment and laser tracker measurement process, using a vertical tail for a civil aircraft as the case-study. This built upon the use of an MTConnect-based monitoring system to overcome the interoperable problems caused by different proprietary interfaces and communication protocols, (Lei et al., 2016).

In the context of this research, a substantial holding fixture and a column-based machine-tool are proposed, see Figure 20, pp 64; both of which this research is seeking to negate the need for, due to their cost and inflexibility. In addition, this approach highlights a potential significant difference between civil and military airframes assembly processes; in military assembly if a metallic surface was machined the protect treatments and primer, applied at detail manufacture, would

need to be re-instated manually, after a time consuming dye penetrant test is performed to determine if the surface contains micro-cracks.

The laser tracker is a commonly used metrology device in airframe assembly, however, it is frequently used in a non-uniform temperature environment, and optimization of its configuration is a core issue, (Peggs et al., 2009), (Weckenmann et al., 2009).

Current global research focuses on integration of measurement with assembly, and the uncertainty in position and orientation (U-P&O) and its influence on quality is ignored (Zhehan et al., 2013). Many sources of variation have been identified, see Figure 21, pp 65, when using optical targets such as Spherically Mounted Retroreflector (SMR).

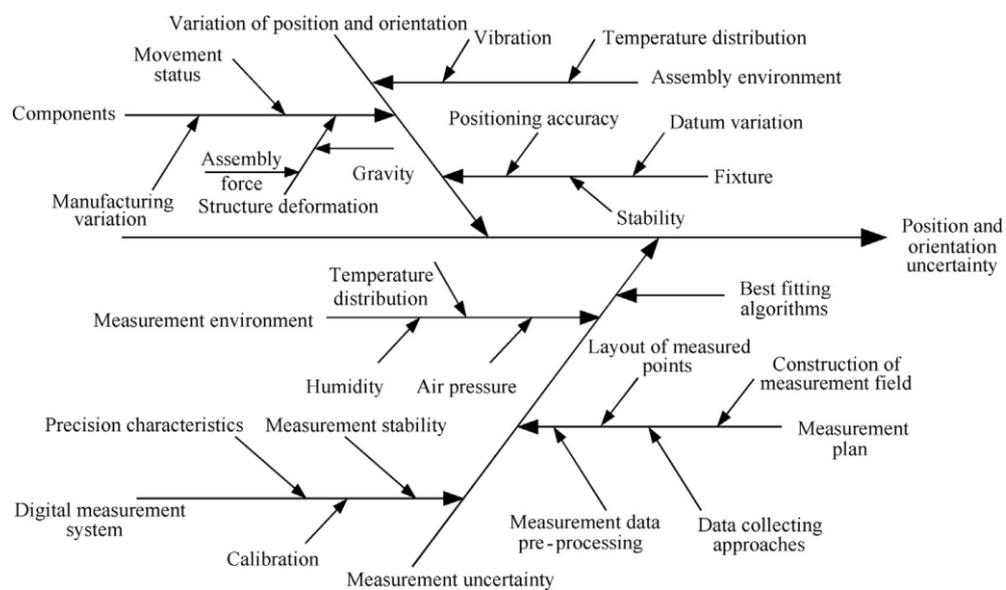


Figure 21: Effect factors of U-P&O in digital measurement assisted aircraft assembly (source: Zhehan)

A measurement plan is required for collecting and separating location uncertainty and measurement uncertainty, with a number of plans required to encompass the different type of measurement equipment, laser trackers, laser radars, optical CMM, etc. The measurement plans will enable the integration of measurement with assembly planning, (Maropoulos et al., 2008), and be part of an overall framework

linking part-to-part assembly methods and measurement assisted assembly, see Figure 60, pp 134.

The impact on this research is that many of the effect factors, see Figure 21, pp 65, are not considered in current UK production facilities, which are very expensive, highly controlled environments. Aspiration for Factories of the Future, which may be less environmentally controlled, will need to account for them by benefiting from I4.0 and the abundance of sensors on 5G private-networks using machine-learning to provide short-term control-loops.

Research has established an improved mathematical model for measuring uncertainty by accounting for the main uncertainty sources, namely the mechanism and non-uniform temperature, and the use of Monte-Carlo simulation to evaluate the uncertainty in different configurations. Then through iterations an optimal position can be obtained, (Zhu et al., 2016). Numerical controlled locators (NCLs) that support and adjust the posture of the assembly, (Williams et al., 2000), and large volume measuring systems such as laser tracker, measure key-points on the parts to verify the posture. Previous work has focused on calibration of the alignment system, (Mei and Maropoulos, 2014), and posture adjustment, (Yuan LI, 2017). The locators use spherical joints to connect to the component, and these have been identified as a primary source of error. Using finite element analysis (FEA), particle swarm optimization, and Monte-Carlo simulation, positional errors have been reduced from 14.2mm to less than 0.4mm, significantly reducing the risk of collision, (Deng et al., 2019). It is also suggested that, since evaluation of relative postures is a common problem in robot calibration, this method provides an alternative.

The impact on this research is the need in the future to identify the errors associated with the different choices of locator or end-feature that holds the part, such as spherical joints, zero-point clamps, etc. as well as the creation of a global frame of reference.

The Stewart platform, or Hexapod, has been proposed as an automated flexible tooling solution (Cirillo et al., 2015), (Erdem et al., 2016a), (Cirillo et al., 2017), as an alternative to robot-based or actuated/active fixtures. Using screw-theory, an algorithm to measure six-dimensional force/torque, including dynamic gravity deviations has been modelled, (Wen et al., 2016). This research would benefit monitoring force/torque dynamically as a method of determining if the addition of a part to an assembly is distorting it; which is not simple using industrial robots due to their stiffness. It is envisaged these devices would be set using a metrology device such as a laser tracker.

4.6.2 Shimming Aero-structures

Shim is used in aerospace to fill gaps between components, its purpose is to reduce the amount of pull-down, and without it the load on the fasteners would be increased, reducing the life of the airframe. Shim can be a paste adhesive, often termed liquid-shim, and is useable up to a maximum thickness, in the order of 1mm. If a thicker shim is required then a solid shim is used, they are typically hand-made and are often associated with a concession.

Predictive shimming, (Kayani and Jamshidi, 2007), (KAYANI and Gray, 2009), is one of the interface management methods used in measurement assisted assembly, (Muelaner et al., 2011a).

Liquid shim is commonly applied manually to one component before a second is located relative to it. The excess shim is squeezed-out, and it must be removed.

Automated application of liquid shim has been researched by most major aerospace companies, as it is a labour-intensive, time-bound task, which requires up to 72-hours to cure before it can be handled; hence there are methods of accelerating the cure by using heat.

Some methods have been developed to automatically apply liquid shim.

Two sets of point-clouds, one for each surface, were measured with reference to the world coordinate system, then using a simulation of the robot cell the gap between the joining parts was derived allowing the correct amount of adhesive to be calculated, (Schmick et al., 2015). The inherent inaccuracies of the industrial robot, work-piece positioning and process tolerances, mean some level of manual

adjustment can be required. These inaccuracies can be reduced so the process tolerances are achieved, (Shah et al., 2018), using on-board vision and laser line triangulation sensors.

Some of the issues with liquid shim are; the cured excess has to be removed often by disassembling the parts, ensuring the shim flows to all the edges requires complex paths, and the adhesives contain fillers which clog standard industrial dispensing heads.

A common approach used is surface scanning, virtual assembly, and 3D gap calculation, (Ehmke et al., 2017), with algorithms deciding which type of shim, liquid or solid, must be applied.

By processing two geometrically non combined point clouds a closed volume model that represents the gap can be created and 3D printed, (Schmick et al., 2016). The printer used was a Stratasys uPrint SE plus, with a maximum build size of 203 x 203 x 152 mm, and layer thicknesses of either 0.254 mm or 0.330 mm.

The point cloud data is often too rich to create 3D models directly, hence algorithms exist to reduce the surface errors, (Schmick et al., 2016), and the volume of data needed requires machine learning and sparse sensing (Manohar et al., 2017).

An alternative approach is to again use a simulated gap volume based on metrological measurements, and 3D print directly onto the composite surface a solid shim made from ABS, (Antolin-Urbaneja et al., 2016), using an anthropomorphic robot. This novel approach was designed for shimming gaps greater than 127 microns (0,005"), using an end effector (50 microns) that was limited by the minimum layer deposition (90 microns).

The point cloud data can be measured by the part manufacturer and transmitted prior to shipping, so enabling the shim to be printed before the parts arrive for assembly, (Schmick et al., 2016).

The literature mainly focuses on wings and other flying surfaces as its use-cases. They are characterised by a large double-curvature contact surface area between a carbon skin and assembled structure, to which historically the shim is applied manually. Shimming the joint has a considerable impact on the aerodynamics of the finished product, and is an objective of MAA, (Maropoulos et al., 2014).

This research looked at the part-to-part assembly of sections of a fuselage, but could be extended to wings and other flying surfaces. The gaps can be characterised as a multitude of small, planar contact surface areas, the size of which is a product of the machine tools used.

Most of the literature uses scanning as the method of measuring the surfaces, then uses algorithms to smooth and reduce the data to create a surface that can be printed. However, it was demonstrated (Manohar et al., 2017), that by using only 3-percent of the data, the gap could be predicted within the measurement tolerance.

This research adopted a similar approach, using measurement methods available on machine tools as standard, and making a limited number of measurements, thereby reducing the burden on data acquisition and downstream processing.

4.6.3 Adopting AM in Aerospace

Aerospace is a highly regulated industry, so while Additive Manufacture is an excellent tool to produce physical models or prototypes, their quality and reproducibility are referred to as its Achilles heel.

Ensuring repeatability and consistency within a build volume, between builds, and between machines is fundamental to its use in aerospace, and other regulated industries such as manufacture of medical devices, (Spears and Gold, 2016).

Despite the numerous advantages of AM, the manufacture of primary structure and mission-critical parts is limited, the primary cause is the lack of technological standards due to the rapid growth of the technology, (Mohd Yusuf et al., 2019). The establishment of standards would ensure, consistency, repeatability, and reliability, reducing the likelihood of critical components failing during service.

A review of the literature on AM layer thickness highlights the complexity of the task of producing the thin layers that are needed when making up shim less than 500 μm thick.

Optimisation of a laser additive manufacturing process for a new material is challenging. Compared to process parameters such as laser power, scanning speed, and hatch spacing, optimising the powder layer thickness is time-consuming. There

is a complex interaction between particle size, the wiper, and build-plate during the powder deposition. Simulation predicted a uniform deposition when the layer thickness (40 μm) was greater than the average particle size (34.4 μm); a thinner layer (30 μm) results in voids, while a thicker layer (50 μm) produces short-feed defects, (Han et al., 2019).

Low layer thickness combined with high feed rate values are recommended for optimal mechanical properties, (Chacón et al., 2017), in extruded thermoplastic filament such as polylactic acid PLA . Due to the layer-by-layer process 3D printed parts exhibit anisotropic behaviour, so build direction is an important consideration.

In laser-powder-bed fusion, the actual thickness of the powder particles spread on the solidification zone is higher than the nominal layer thickness; this is to accommodate the shrinkage that occurs after selective melting followed by solidification. Termed the effective layer thickness (ELT), for 17-4 PH stainless steel to create a nominal 20 μm layer the ELT was greater than 100 μm , (Mahmoodkhani et al., 2019), which is far greater than values reported in the literature.

4.7 Gap Analysis

The review of the literature in this chapter has allowed a number of gaps in the field of automated assembly in the context of the military airframe to be identified. These gaps are:

- Evidence suggests MAA has not been applied to fast-jet airframes
- The assembly of structure or sub-structure has been ignored
- One-way, Determinate, and Interchangeability drilling during the manufacture of the parts
- Part-to-part shimming based upon process capability, measurement and additive manufacture.

4.7.1 Evidence of Measurement Assisted Assembly

Based on the literature reviewed, as well as knowledge and experience of airframe assembly, measurement assisted assembly has not previously been applied to the assembly of a fast-jet airframe. It is generally accepted that the parts of an airframe

cannot be manufactured economically and accurately enough to allow them to be assembled and achieve the demanding tolerance set; hence in assembly the parts are fitted together in a fixture, and machine tools are used to cut the surface accurately. Therefore there is a gap in the knowledge of assembling a fast-jet airframe, specifically that of using measurement to assist. There are four key MAA technologies, namely Predictive Processes, Assemble-Measure-Move, Active Tooling, and Closed-loop Control.

In this research a variation of the predictive shimming process will be applied to the additive manufacture of shims, while move-measure-correct (MMC) will be applied to industrial robots to locate parts relative to one another with minimal fixturing.

4.7.2 Assembly of the structure

Both in the literature and internally at BAE there has been a tendency to focus on the assembly of the skin to structure, primarily to achieve the aerodynamic tolerance needed for fuel economy on civil airliners and outer mould line control on military fast-jets. In military manufacturing this has driven the use of very expensive machine tools, something that is impractical due to scale in civil manufacturing. Very little research has focused on the structure as a whole; some aspects such as attaching brackets to a spar have been explored, but not assembling one part to another using measurement.

This research has focused on using automation, such as metrology guided robots, additive manufacture of shim, and pre-drilling of parts, to explore the assembly of a structure; with the option of extending the methods to assembling the skin to structure too.

4.7.3 Part-to-Part Drilling

Part-to-part assembly identified six methods of assembling aircraft parts, from the traditional approach in a fixture to the completely interchangeable / determinate assembly approach that needs no fixtures. Each approach uses a different drilling process, and an assembly can use one or many of them. This research examined two methods, one-way and interchangeable. One-way was used on IAAD while interchangeable was used on IAAD 1B. Between them lies determinate drilling which is the next logical method to explore, but was beyond the boundaries of this research.

4.7.4 Part-to-Part Shimming

Finally, there is limited literature on designing gaps in large, flexible assemblies to accommodate the inaccuracies in the parts due to their method of manufacture, and using data collected during their manufacture to drive the additive manufacture of shims that fill the gaps so locating one part relative to another, negating the need for a fixture.

In this research the size of gaps between the parts will be based upon the available manufacturing capability data, and parts will be measured during their manufacture. This will allow the parts to be virtually assembled, and shims manufactured using an additive processes. The aim will then be to install the shims to locate one part relative to another, to within standard tooling tolerance, creating the opportunity to assemble manually, collaboratively, and automatically.

5 Progression towards Automated Assembly

5.1 Introduction

This research has contributed to a number of internal projects at BAE over its 5-year duration. A chronology of all the projects is shown in Figure 22, pp 73, with those closely linked to BAES internal, unpublished reports highlighted for reference.

This chapter describes a project called Integrated Autonomous Assembly Demonstrator (IAAD), and a follow-on smaller project called IAAD 1B, which have led to the establishment a factory of the future on BAE's Warton site.

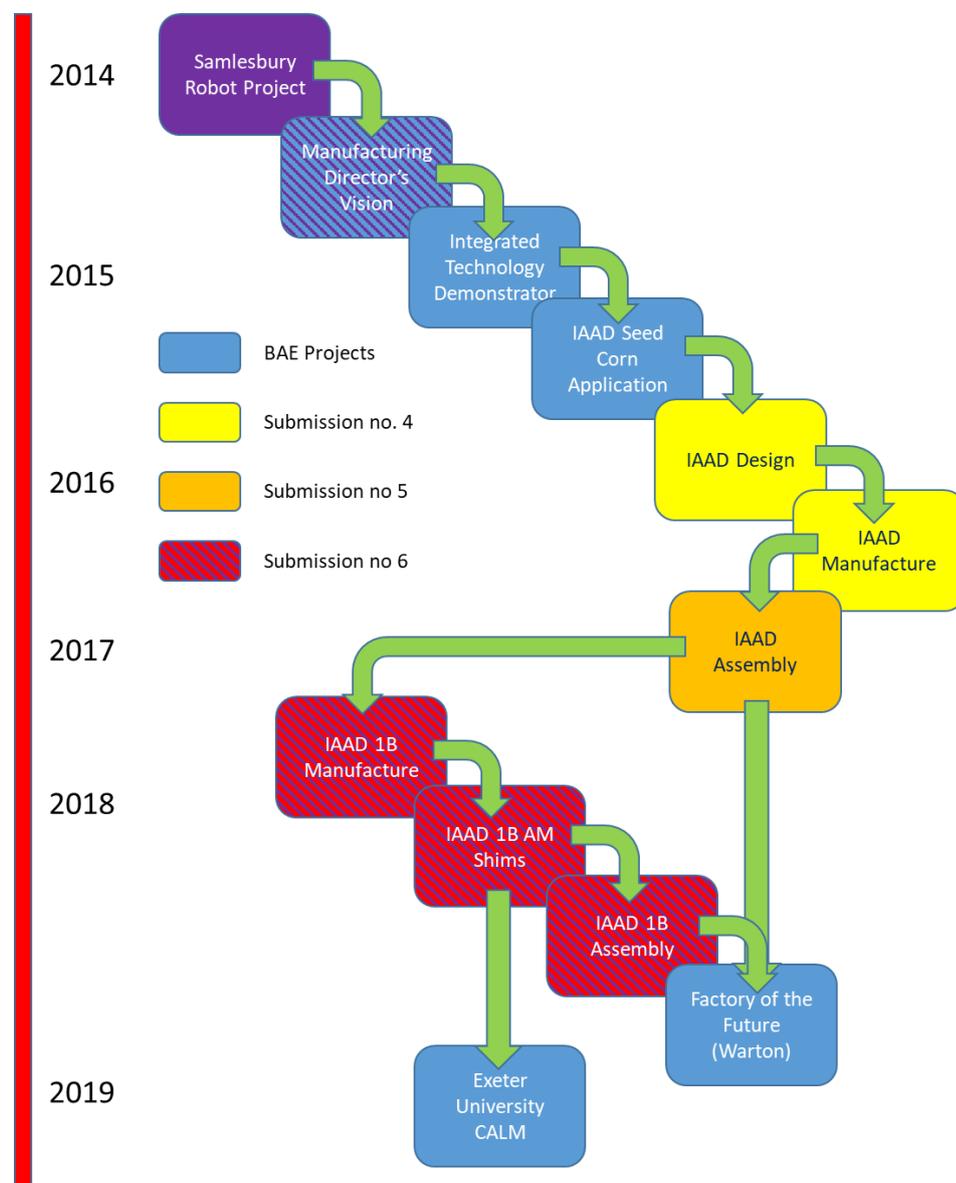


Figure 22: A Chronology projects and sub-projects linked to this research

The chapter is divided into the following sections:

- A brief description of the background that led to the creation of the IAAD project,
- The design process followed to produce the IAAD CAD data,
- The manufacture of both carbon and metallic parts for IAAD and IAAD 1B,
- The assembly of IAAD at Nottingham using robotics, and the assembly of IAAD 1B at the AMRC using predictive shimming and part-to-part ICY/DA drilling, and
- A summary of the achievements, and their impact on innovation and the factory of the future.

5.2 Background – Manufacturing Director’s Vision

In 2014 the Director for Manufacturing described his vision of airframe assembly in the future. It was portrayed as a highly flexible system that would reduce start-up investment, cycle times and production costs see Figure 23, pp 74.

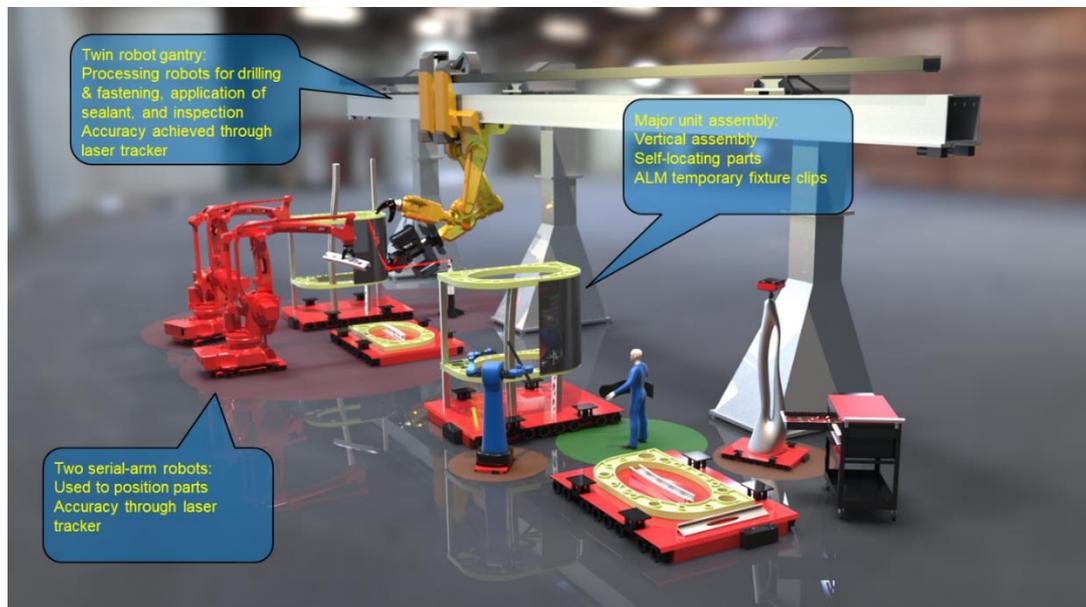


Figure 23: Future Airframe Assembly (source: BAE Systems)

The vision was an amalgamation of robotic and automated assembly philosophies, with an emphasis on the use of data to create an intelligent, integrated, highly adaptable, re-configurable system.

5.2.1 Partnerships – University of Nottingham

At the same time as a strategic global industrial partner of the University of Nottingham (UoN) BAE were given sight of a future demonstrator called Future Automated Aircraft Assembly Demonstrator (FA³D). The scope of FA³D closely matched the aspirations of BAE so negotiations started to determine how the two parties could collaborate.

5.2.2 Funding Mechanism – Seed Corn

Changes within the organisation at the beginning of 2015 enabled an investment fund to be created and administered from head office by Nigel Whitehead, Group MD of the UK defence businesses.

The fund called the Seed-Corn investment fund was designed to stimulate the production of longer-term potential future products and provide support to the longer term, or higher risk, options that are critical for success but which are difficult to execute within the current Lines of Business (LoB).

5.2.3 Integrated Autonomous Assembly Demonstrator

Mid-2015 an application was made to the Seed-Corn fund for a project called Integrated Autonomous Assembly Demonstrator (IAAD), whose top-level objective was:

“... to demonstrate the effective use of fully-integrated robotics and automated assembly philosophies, and their ability to achieve outer mould line control by manufacturing a representative airframe demonstrator product.”

The application stated that a new product would be designed in-house, with the parts manufactured at Samlesbury in its 3B Machine Shop and Special Engineered Composite Facility (SECF); they would then be shipped to the University of Nottingham, where they would be assembled in the FA³D cell.

The aim was to validate a number of technologies and philosophies that collectively would deliver a step-change in the Military Aircraft & Information (MAI) manufacturing systems, and necessitate a corresponding change to the established Engineering standards and principles.

The key dates in the proposal were:

- The project would be a 16-month programme, to be completed by the end of 2016
- The University of Nottingham cell would be fully established by January 2016
- Assembly of IAAD would commence by April 2016

The medium-term objective, aligned to future programmes, was given as, all technologies to be developed to Technology Readiness Level (TRL) 6 for a potential design freeze in 2019. IAAD did not have to demonstrate TRL in isolation but was the first phase of a multi-phase approach planned by the company.

5.2.4 Project Launch

The project was launched in August 2015, and the project team including the University of Nottingham was formed. They were tasked with delivering IAAD against eleven key principles or performance indicators (KPIs) that challenged the existing norms within the company, see Table 2, pp 77. These KPIs were prioritised (primary, secondary, tertiary) and a short description of how they would be demonstrated was provided.

KPI	Description	Priority
1	Robotic assembly of primary airframe structure	Primary
	<i>Primary structure will be positioned by robots. Two major sub-assemblies will be manoeuvred by robot. One sub assembly will be positioned by robot.</i>	
2	Demonstrate enablers to achieving tolerance requirements utilising industrial robotics.	Primary
	<i>Vision measurement system will feed back into robotics to achieve required build standards.</i>	
3	Significant reduction in the need for bespoke hard-tooling .	Secondary
	<i>75% of traditional major assembly jigs have been replaced with robotics.</i>	
4	Self-determining parts and features.	Tertiary
	<i>Shear webs and floors will contain full size accurately positioned bolt holes which will be used to position these parts.</i>	

KPI	Description	Priority
5	Additional utilisation of robotics for measurement, drilling and fastener installation	Tertiary
	<i>All the structure will be measured via the vision system - Diverter panel will be positioned, drilled with fasteners installed by robotics.</i>	
6	Dynamic, 'real-time' shim process , utilising additive manufacturing of solid shim.	Secondary
	<i>Diverter panel shim requirement will be assessed using the vision system. ALM will be used to produce appropriate shims for assembly.</i>	
7	Use of wireless technology to identify and convey engineering data	Tertiary
	<i>RFID tags will be attached to all parts with information including part number, issue, part location, inspection data, and status.</i>	
8	Demonstrate safety aspects associated with integrated robotic co-working.	Tertiary
	<i>Build philosophy supports the investigation of legislation and SHE issues resulting in knowledge of what is currently possible and what needs to be resolved.</i>	
9	Exploit enabling technologies such as virtual reality, 'Big-Data' and real-time mobile / web enabled technology.	Tertiary
	<i>Cell set-up contains vision system and programmed robotics, data from which will be captured and used for the build. Cell layout and build philosophy will be demonstrated in the Samlesbury 3D VR room. Part data will be captured via RFID tags.</i>	
10	Demonstrate ability to achieve OML control.	Primary
	<i>"Get for free" build philosophy investigates alternative assembly methods while achieving the appropriate build standard using a flexible cost effective approach.</i>	
11	Demonstrate Flexibility to manufacture multiple structures in one cell.	Primary
	<i>Cell is used to manufacture 2 sub-assemblies and 1 major assembly. Same set-up can be used to build units from same or other project – FA3D, wing, fuselage side assy.</i>	

Table 2: IAAD Activities and their Demonstration

The priorities were set to help guide the University of Nottingham during the early part of the project while the assembly philosophy was being developed and the cell was being commissioned; it was an indication of what the company saw as key to understand at that point in time.

5.3 Design

Currently airframes are designed to be assembled in traditional fixtures, using craft-based processes and machine tools, by designers who are guided by a technical standards manual that defines the manufacturing processes available. Currently there are no robotic or automated assembly related guidelines.

Designs are highly engineered from a functional perspective, with the priority given to the aerodynamic shape and load-paths through the airframe, so there is little opportunity to start with a modular design to which bespoke features can be added.

On the Typhoon project there is a single size of gap between the metallic parts that make-up the structure. The origins of which are vague, but given the fact that it is a 1980s/1990s design, and the capability of a process as part of the lean culture had not yet been introduced, it will not have been based on machining capability.

Aerospace is a highly regulated industry, and this extends to the design process.

5.3.1 Design for Robotic Assembly

Part-to-part assembly is the forming of parts pre-assembly, allowing them to be assembled just the once, rather than the traditional method that involves fitting not assembling them, and all the associated non-value added activities.

As identified in the literature review of measurement assisted assembly (MAA), part-to-part (P2P) assembly should not be applied to an existing design except for the traditional assembly method. The complete structure should be divided into parts and sub-assemblies, then for each design tolerance analysis and optimisation should be used to determine which of the six build paradigms, see Figure 24, pp 79, are achievable.

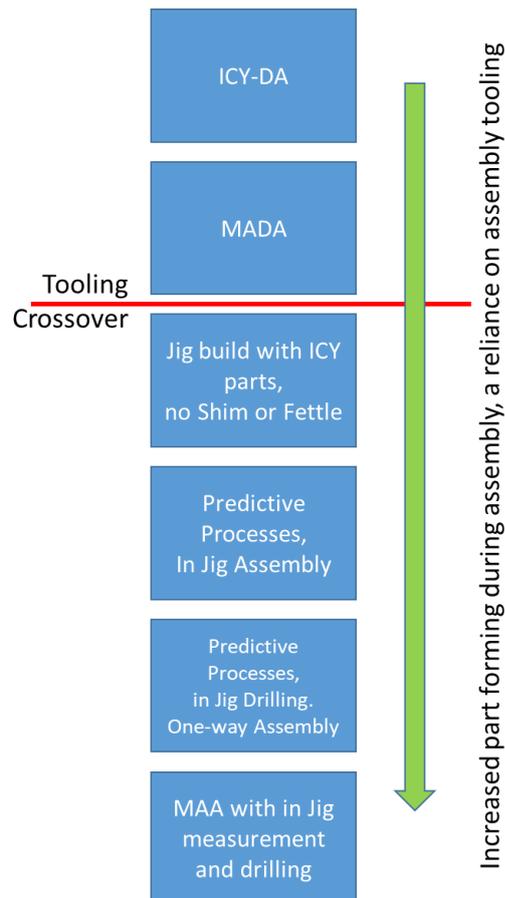


Figure 24: Part-to-Part Assembly Paradigms

As illustrated in Figure 24, pp 79, there is a hierarchy of assembly paradigms, from the ideal that uses interchangeable parts and simple tooling to the traditional use of craft-based skills in a conventional fixture. Each paradigm requires a design configuration to be generated, with tolerances added and optimisation (Shi, 2006) (Mazur et al., 2011). The progression from the most to the least preferable paradigm represents an increasing amount of component forming occurring during assembly and an increased reliance on the use of tooling.

As discussed previously in Section 4.5.6, pp 59, a novel design was necessary to enable the use of measurement assisted determinate assembly (MADA) on a wing box.

BAE has a design process that is part of the company's overall life cycle management framework, which follows the IEEE standard 15288.2 for technical reviews and audits on defence programs. The process is built on traditional assembly methods that use approved processes which are documented in the

Technical Standards Manual (TSM). Through a series of gate reviews, the design process creates 3D models and 2D drawings using Dassault Systemes' CATIA v5, and stores them in a file-based archive. The designers of IAAD used the TSM for quality assurance, except in two instances, how the part would be held by the robots and the sizes of the gaps between the parts; this was because the TSM does not currently have design guidelines for either, designing parts to be held by a robot or calculating the size of the gap between parts based upon statistical process capability.

5.3.2 Modular Design

IAAD was based upon a typical centre-fuselage for an unmanned air vehicle (UAV). It was slightly simplified, in that it's only external surface was single curvature, but this allowed the design of a sub-assembly, comprising shear-webs and a floor, to be symmetric about the centreline and then repeated three-times; enabling modular assembly with bespoke fitting to accommodate the seam-map of the skins. The skins were designed to be a constant thickness and manufactured from carbon fibre using the resin infused moulding (RIM) technique, while the structure would be assembled from machined aluminium parts.

Quite early in the design process the assembly methodology was requested by Design [function]. There had already been a decision made that IAAD would be built vertically, to minimise its foot-print, so the trade-study was defined as how to locate four-frames and insert the shear-webs and floors that joined them together in a vertical orientation. Three methods were proposed by BAE, the "haystack" – building one layer upon another, the "sky-scraper" – build one layer, raise it, then assemble to next below it, etc., and finally, the "layer-cake" – build one layer then put it aside, build the next, and bring back the first and join them.

The advantages and disadvantages for each method were discussed, in conjunction with Nottingham University, and the "layer-cake" method was chosen for the following reasons; fixed optimum working height, better access, perceived to be "pushing new boundaries. It was the option with the fewest technical issues, see Table 3, pp 81, for details of the other options.

Options	Hay-stack	Layered Cake	Sky-scraper
Description	Building layer upon layer, starting at the lowest layer first, and working upwards	Building the top layer & setting it aside, then building the lower layer, before picking up the top layer again, positioning it over the lower layer, and joining the two layers together	Building the top storey, lifting it, building the middle storey beneath it, lifting again, and building the lower storey
Pros	The structure doesn't move (traditional)	The manual / robotic workspace can be fixed at optimum height Better access Pushes boundaries Many differing aspects	The manual / robotic workspace can be fixed at one height
Cons	The manual / robotic workspace gets high with each layer, so requiring use of staging Not challenging	Jig stand has to be reconfigured to maintain working height	As each layer is completed it is held above the next layer
Safety Issues	Working at heights	Suspension of top layer above the lower layer, while the mid-layer is constructed	Suspension of top, then top and middle storeys over the next storey
Technical Issues	Robot reach, particularly inner shear-web, on lower and upper layers	Option with least perceived issues	Increasing weigh, always on the robot arm
Recommendations	This is the fall-back option, if required	UoN & BAES preferred option	Not recommended by either UoN or BAES

Table 3: IAAD Assembly Philosophies

The generic approach to assembling a layer was schemed, as per Figure 25, pp 81. The key points about that decision were, creating a common work zone for both operator and robot, demonstrating the assembly of modules and their customisation, and the reconfiguration of the cell with each robot undertaking more than one task. Demonstrating these points also satisfied some of the KPIs, as outlined in Table 2, pp 77, and in the funding application.

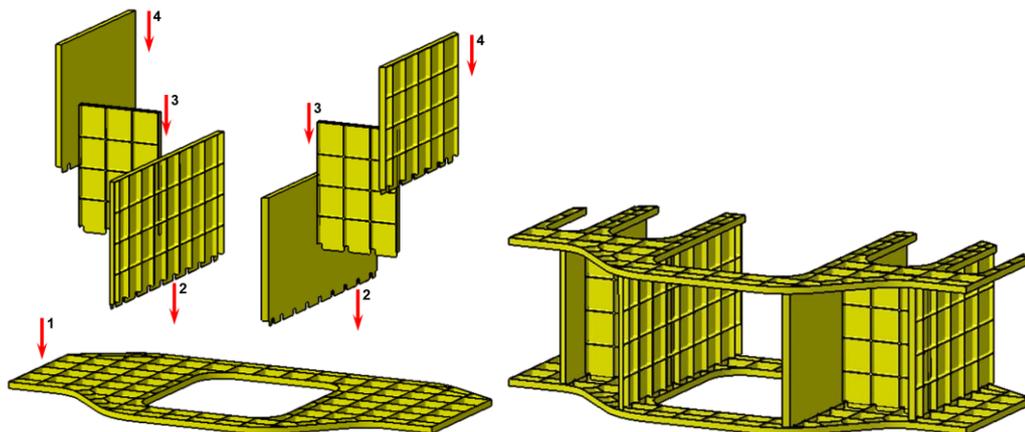


Figure 25: Initial Scheme – Generic Assembly of a Layer

At the same time as the assembly methodology was agreed the method of locating (or positioning) the parts was agreed too. The proposal involved using one metrology system to guide the robot and a second to check the end location of the part. The robots would use interchangeable end-effectors, assembled from a commercially available modular system, and have a zero-point clamping system to hold the parts. The only restriction was the diameter of the zero-point clamps, at 80mm diameter there were restrictions on which pockets could be used, and where in a pocket a tooling hole could be placed. Traditional fixture design is not so restrictive, as everything is bespoke.

The generic positioning process for a part was outlined as; unguided a robot would position a part approximately 10mm from its CAD nominal location, a metrology system would then assume control and guide the robot until the part was at the desired location to within a tolerance. This process influenced the type of joints used in the design – lap or butt, and the sequence the parts would be installed in; all the joints were formed with a 10mm translation, there were no rotations such as locating a shear-web between two installed frames.

5.3.3 Gaps between Parts

The second deviation from the TSM was the size of the gap between the parts; gaps are included so assemblies can be built stress-free, and a legacy of all metal airframes which need fitting together. One of the KPIs (no. 6) was the use of Additive Manufacturing (AM) to create shims, which would negate processes used on current programmes that use sacrificial materials, fettling, and machine tools. The Typhoon design standards are, a single size of gap between all jig-located metallic parts, and a percentage based on the thickness variation in carbon-fibre between the skin and structure. Various anomalies were noted in these standards; the size of the gap was, allegedly, based on two layers of paint/primer and a layer of sealant, but the sum of their maximum allowances is less than the nominal gap. The 3D models are drawn un-painted, which is fine for inspecting the details during their manufacture but the modelled surfaces cannot be measured after painting during assembly. Finally, the gap is a negative solid or void in the model, which is problematic when trying to undertake tolerance analysis using packages such as Siemens' Variation Simulation Analysis (VSA); it attempts to close the gap while the part is restrained, therefore distorting it.

In calculating the size of the various gaps for Design [function], an analysis of the joints showed there were two types, lap and butt. Lap-joints had one interface that varied due to the manufacturing process, and the other interface was a datum-face (and only varied by the thickness of the paint/primer). In a butt-joint both interfaces varied due to the manufacturing processes used, and the opposite side on one of the two parts is a critical surface, such as the OML surface of the skin.

There are three primary sizes of gap, see Table 4, pp 83:

Joint Type	Variation (mm)	Constants (mm)	Design Gap (mm)	Shim Range (mm)
Lap-joint	± 0.20	0.14	0.34	0.00 - 0.40
Butt-joint ⁴	± 0.34	0.14	0.48	0.00 – 0.68
Skin to Structure	± 0.39	0.11	0.50	0.00 – 0.78

Table 4: Design Gap and Shim Range

All the lap-joints occurred between the shear-webs or floors and the frame. By making the datum face on the shear-webs or floor, only the variation in the frame effected the size of the gap, which also simplified the inspection requirement.

The webs and stiffeners on the metallic parts were designed to standard nominal thicknesses, but there was no mass optimisation. This made manufacture of the metallic parts simpler, for example, the radius in the bottom of the pockets was 8mm rather than 4mm so easier to machine, and the landings around the tooling holes were a constant thickness over the whole of the base of the pocket rather than the traditional raised boss.

Even though the design was not mass optimised, the picking and placing of each layer and the rotation of the assembled layers was scrutinised by Weight and Structures engineers. They calculated the minimum number of fasteners that needed to be installed to ensure a safe lift and rotation from a product safety perspective.

The idea of Meccano™ build was also considered; it equates to the ICY/DA build paradigm in the spectrum of P2P assembly methods. But it was only considered for the P2P fastener holes in the structure. It reflected an aspiration to drill as many

⁴ Assumes part-to-part location, and fixture location was ± 0.36 mm

holes as practical during the manufacture of the details, reducing drilling on assembly and saving touch-labour. Currently, the tolerance on the fastener holes remains H11 (+0.000/+0.075). Neither ICY/DA or MADA were used as they both require holes to be drilled full diameter, instead a variation on one-way assembly was proposed whereby the holes would be drilled under-size, and drill/reamed to full diameter without requiring to disassemble and deburr. This was discussed during the design reviews as it changed the condition of supply (CoS) of the parts as well as requiring a new machining processes, the use of an angle-head drill unit. It was allowed only because it was a demonstrator, and it is not a production process.

5.4 Manufacture

This sub-section of the report covers the manufacture of parts for both the IAAD and IAAD 1B demonstrators. All the parts were manufactured from the same CAD data, hence there was no mention or discussion of IAAD 1B in the previous section on the design of IAAD. IAAD 1B was one of three follow-on projects from IAAD based upon the findings. The other two investigated metrology systems in general, and automated sealant application; neither of these projects will be discussed in this report.

IAAD 1B was undertaken in response to what were classed as deficiencies that resulted in no evidence based conclusions being made for three KPIs; those KPIs as originally defined, see Table 2, pp 77, are listed below:

- No. 4: Self-determining parts and features
- Elimination of ‘strip-down & de-burr’
- No. 6: Dynamic, ‘real-time’ shim process, utilising additive manufacturing of solid shim

The deficiencies were; not measuring the parts during manufacture, therefore no shims could be made in advance and a method of locating one part to another was not demonstrated. The limitation in the diameter of the angle-head drilling units (4.1mm) prevented full-diameter holes from being drilled, so no “strip and deburr” was only approved because IAAD was a non-flying test article. Finally, with insufficient measurement data, and no prospect of acquiring it using traditional

methods (i.e. feeler gauges), the part-to-part shims could not be manufactured using an AM process.

5.4.1 IAAD Metallic Parts

An assumption made in the proposal was that the design would only require 3-axis machining, that was changed when the flanges and landings under the skins and panel were reviewed and it was determined that the shear-webs would need closed angles that could only be created on a 5-axis machine.

The initial scheme was based upon single-sided frames, and to manufacture the parts, three tooling grades of aluminium were initially considered (5000, 6000, and 7000 grades), due to their availability and cost. While acceptable to Design, the Machining group had reservations about the machining characteristics, so undertook trials to determine the machining parameters.

Through the design review process, an alternative specification of material, EN3982, was proposed which did not need require any trials, and was available in a greater range of sizes and thicknesses. This enabled double-sided frames, which are thicker, to be introduced, and they in turn enabled the design to be simplified; the forward and aft joints were the same.

A set of billets including prep to locate them directly onto the machine tool bed were ordered to manufacture IAAD but there were none for tape-proving. While BAE has world-class machine shops, the factory systems are not configured to manufacture one-offs, and the current CAM process relies on tacit knowledge and up to 5 test articles to produce a first-article part.

The CAM task was undertaken using CATIA V5, and with over 100 pockets per side the frames are complex items. The decision about the order in which to machine the pockets is tacit knowledge, as is which routine and cutter to use which then dictates the spindle speed and a feed-rate.

The machining was done on DST Ecospeed HPA machine tools, which have a mist rather than the traditional flood coolant system. A consequence is the heat generated during the milling of the pockets is absorbed by the part causing it to expand. While the heating effect can be compensated for in the controller⁵, this is tacit knowledge

⁵ [Siemens: Industry Mall - Temperature Compensation](#)

that is part specific. The parts were all machined in-house, and it was unfortunate that they all distorted and needed straightening, either by penning or wheeling. As a result they were not inspected due to miscommunication and a belief that the data would be used to understand machine capability rather than used to demonstrate predictive shimming.

The structure fastener holes were drilled at a detail level, using both conventional and angle-head drilling methods. It had been decided to investigate one-way assembly by drilling to a diameter that would enable an assessment and which could be enlarged without disassembling to deburr. The largest diameter available on an angle-head unit was 4.1mm in a stub-drill. The overall size of the drill and angle-head unit allowed access to every pocket in the frame, so all fastener holes were drilled; it will be explained in a following section of this chapter, but this was not possible on IAAD 1B. The angle-head units have a complex manual setting procedure, which is due to the method of controlling the machine tool spindle's position, therefore once set the preference was to complete all drilling; this highlights the current fragility of the process in house, and the need to undertake further development activities.

All the machining and drilling of the parts was completed before they were treated and painted. Some of the treatments were applied by-hand, and the fastener holes were not plugged so their diameter was slightly reduced due to the ingress of paint, see Figure 26, pp 86.



Figure 26: Paint Ingress of Fastener Holes (source: BAE Systems)

5.4.2 IAAD Carbon-fibre Parts

The three carbon parts were manufactured in the SECF at Samlesbury on mould tooling specifically designed to the outer mould line (OML); the symmetry of the design and the single curvature of the external surface meant only one tool was required to manufacture both fixed skins, see Figure 27, pp 87.



Figure 27: IAAD Fixed Skins Mould Tool

The panel was manufactured using a separate tool. The process used was vacuum resin infusion; dry fibre was laid on the mould tool and consolidated under vacuum before the resin was infused. The parts were then oven-cured and debagging. The untrimmed parts were measured using a pair of callipers with a deep throat, which is not an accurate method. This meant the parts would need to be scanned at assembly to create the shims.

The literature review highlighted MARA, see Section 4.5.5, pp 57, as a potential process to machine the edge of part of the carbon parts, but a prior project had investigated the use of a 5-axis water-jet, so it was agreed to trial that process with low-cost, single-use tooling, see Figure 29, pp 88.

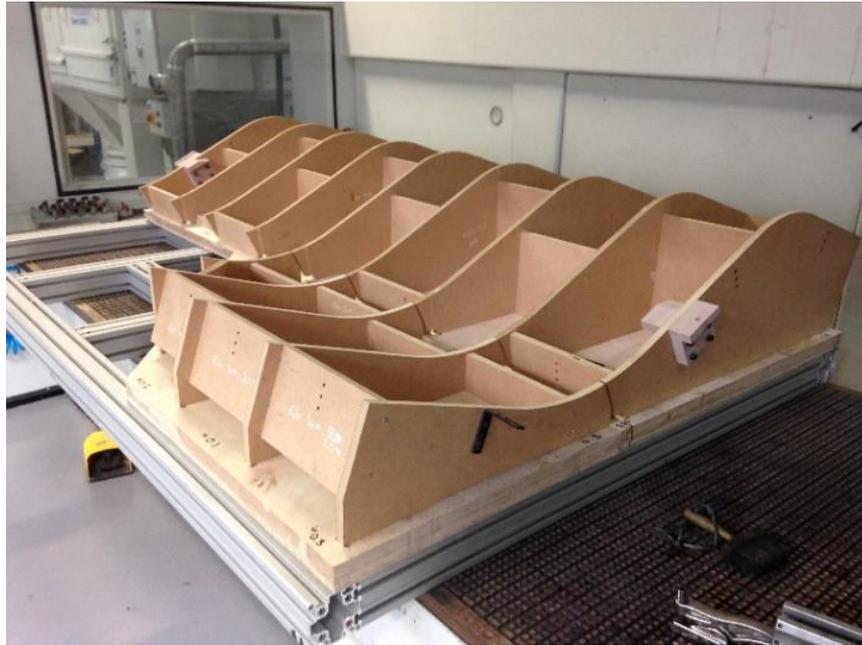


Figure 28: Left-hand Fixed Skin Rout Fixture Assembly

The previous project had not required a datum scheme nor accurate alignment of the part to the machine datum; as a result the first part was scrapped and needed to be re-made. A root-cause analysis was undertaken, with a number of recommendations made, the key ones were:

- Create a whole-process route card, with confirmation and sign-off for each stage.
- Manufacture a more rigid base for the fixture, and seal to prevent water ingress.
- Create a new datum scheme, and a method of aligning the part to the head.
- Nozzle offset, 2.5mm above the surface, to be based upon part thickness, not nominal, and feed rate to be limited to 500 mm/min.
- Where practical, all setting-up, cutting and inspecting, to be done in one day.

When the recommendations were acted upon, the edge-of-part was produced to $\pm 0.50\text{mm}$. The method used was to start with a 20mm off-set, and reduce it in 4-stages to zero.

The carbon parts did not require finishing i.e. painting, and were shipped direct from the AMRC to Nottingham.

5.4.3 IAAD 1B Introduction

The main recommendation from the IAAD project was to remanufacture and assemble one layer of IAAD to further investigate predictive shimming and drilling the fastener holes full diameter at the detail stage to achieve ICY/DA assembly. The project was called IAAD 1B.

5.4.4 IAAD 1B Metallic parts

A set of billets were ordered to manufacture the forward section of IAAD, which comprised of two frames, six shear-webs and two floor, plus two angled supports. Due to the difficulties of manufacturing and inspecting the IAAD part internally the decision was taken to manufacture them at the AMRC, on a machine similar to that at BAE Samlesbury; this would allow some level of post-manufacture comparison to be made. The main difference between the two machines was the AMRC used flood coolant, while Samlesbury used a mist-system; it was believed the mist system had been a contributing factor to the distortion of the IAAD parts.

The AMRC were also used to producing one-offs, and had access to the latest CAM software, which BAE production processes do not. Critically the AMRC had also developed the use of finite element analysis (FEA) a software package to determine the order the pockets in a part should be roughed out, reducing the distortion of the part due to the residual stresses, it is very time efficient; analyses of the frame with 100 pockets took approximately 2-hours, compared to using tacit knowledge and up to five test-pieces.

Stock sizes of billets is an important consideration, due to the high percentage of waste produced by machining. Billet prep, machining them flat and drilling location holes, removed 16-percent by volume, from the stock sizes. Prep reduced a stock billet for a frame from 1102kgs to 1043kgs, from which a 38kgs part was made; 96% of the billet was turned into swarf, hence recycling and waste-streams are an important consideration.

The fixture used was a simple plate, see Figure 29, pp 90. On one side all the single-sided parts were held in place using vacuum and peripheral bolts, while on the other, the double-sided frame was held initially using 70 x M16 bolts, then 8 x Ø10mm bolts through the part's tooling holes.

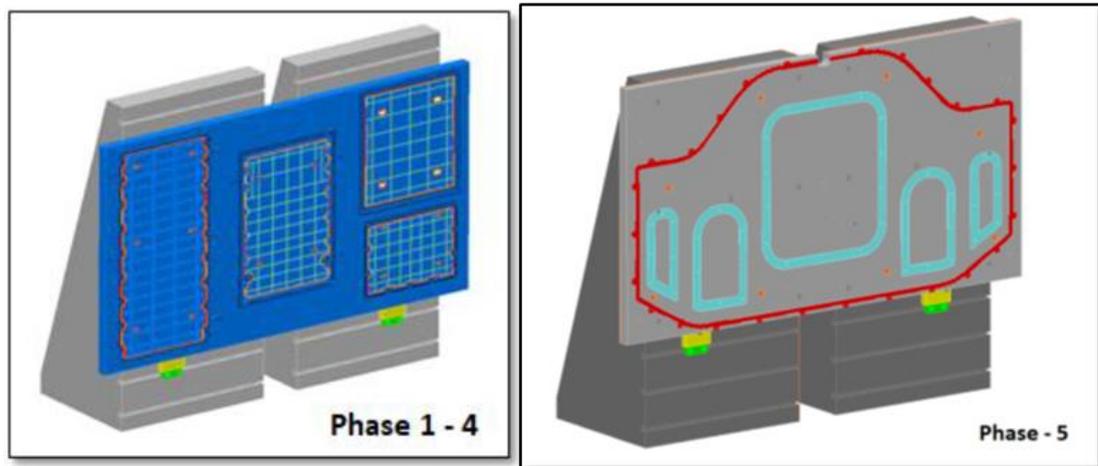


Figure 29: Machining Fixture, Both Sides

Before machining the frames and the other parts, a trial was conducted to determine the best method of producing the pockets, which was the most accurate, and which had the best surface finish.

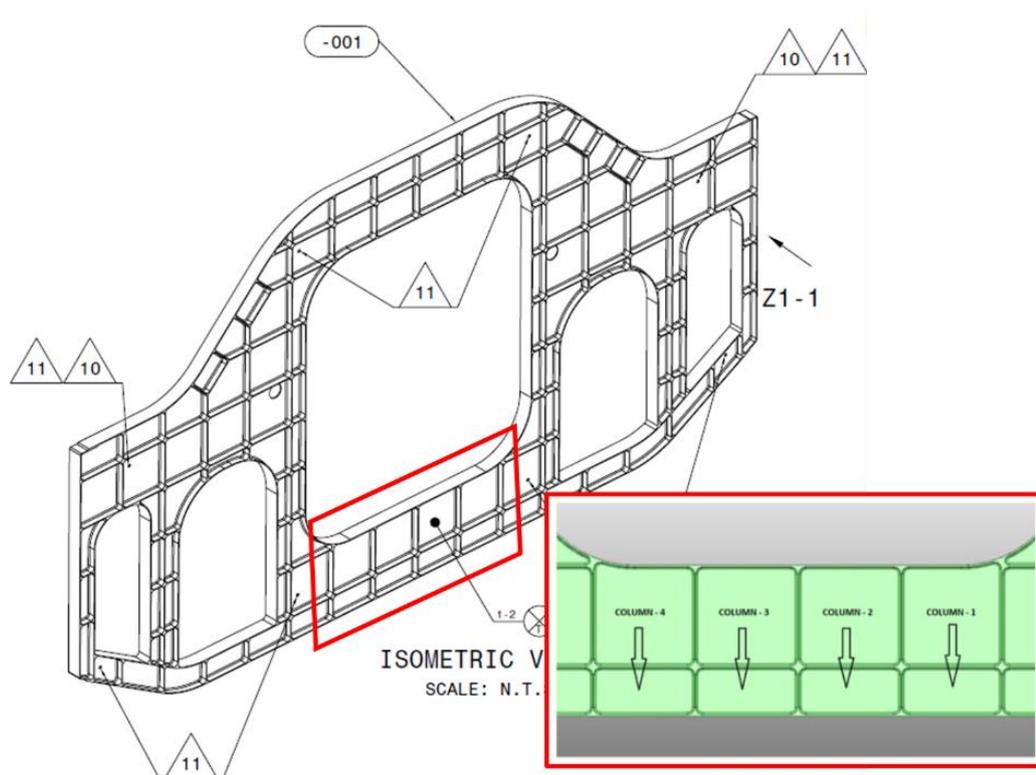


Figure 30: Trial Pockets

Four pockets, similar to those indicated in Figure 30, pp 90, were roughed leaving +2mm, +3mm, +4mm and +5mm, on the floors and +2mm on all the walls, then finished using different Autodesk PowerMill machining strategies and parameters.

The best result was adjudged to be achieved using the strategy and parameters from the +3mm trial.

The frames were roughed starting in the centre of the pocket using an offset flat finishing strategy, while for the other parts roughing started at the edge of the pocket using 3D Offset Finishing with Toolpath Ramp Engagement.

The roughing strategies were repeated to finish the bases of the pockets, while the walls were finished using the Corner Pencil Finishing strategy with horizontal “Arc On and Off”.

Routing cards were produced for roughing and finishing each part. They described each operation, starting with probing the datum hole in the fixture to align the part program, assembling the tools using a tool pre-setter, then loading and securing the prepped billet. The tapes were run with operations to rotate the part if necessary, and a finishing operation to identify each part, distinguishing left-hand parts from right-hand parts, as well as front from back of the frames.

It was also decided to inspect the parts on the machine, using the resident probe and a software package called MSP, which BAE has installed on all its machines. The probe’s performance was tested using MSP’s NC-Checker software, which runs a series of tests that are equivalent of the probe performance tests from the CMM standard ISO 10360.

Unfortunately the machine had a kinematic rather than a strain-gauge probe; they are acceptable for probing a fixture to align the part-program, but the tension on probe to prevent false trigger increases the pre-travel variation making them less accurate. Pre-Travel Variation is a performance check similar to “probe performance overall” except it only uses data from the equator of a sphere. It is a measure of the variation in the amount the probe travels when in contact with the surface before it triggers. For kinematic-type probes the pre-travel variation worsens as the tension on the probe is increased, something often done to prevent false triggers when the machine tool moves quickly; a fact often lost on the user.

The pre-travel variation, for the probe used, has a characteristic tri-lobed error form, Figure 31, pp 92.

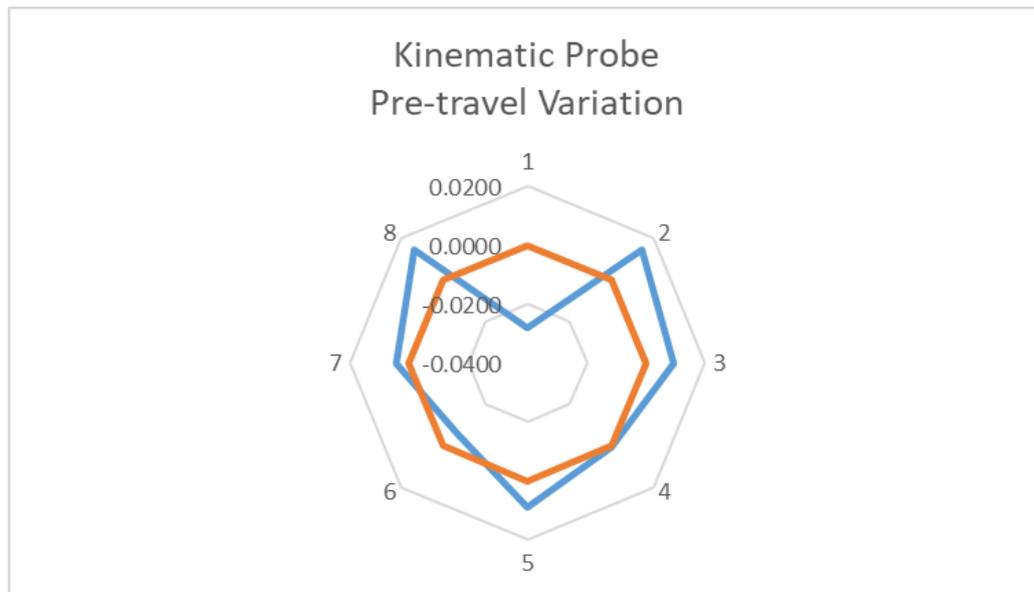


Figure 31: Tri-lobed Error of Resistive Probe

To compound the problem there were data collection issues, resulting in the data needing to be collected a second-time, and subsequently manually manipulated to be usable.

The parts also needed treating and painting, however the size of the frame was problematic; local companies did not have treatment baths large enough. There was also the perennial problem of manually spraying and controlling the thickness, as well as keeping any finished or near-finished holes clear of paint. The frames were shipped to an approved supplier on the south coast, while the shear-webs and floors were accommodated locally. The task of keeping the holes clear of paint was reduced to just the jig-location holes by scheduling the drilling of the fastener holes after painting. In the future the size of parts and the application of the treatments are likely to impact both the assembly methodology (splitting frames due to their size) and the detail manufacturing process (returning the parts after treatments to be drilled); as well as need to comply with the 2007 EU REACH regulations.

The parts were drilled after they had been treated, using both conventional and angle-headed methods; the angle-head unit was used almost exclusively on the frames due to the use of lap-joints. A benefit was all the holes were drilled in a single set-up, so improving the accuracy of one row of holes to another; the greatest inaccuracy or source of error is the alignment of the part to the machine, the pitching of the holes tends to be extremal accuracy as demonstrated on F-35 with the

independent drilling of skin and structure. The angle-head units at BAE had a diameter limit of 4.1mm, so a new head was specified, purchased and installed on the AMRC machine. The drills needed were special drills, termed “Dreamers”, which drill and ream each hole in a single-shot negating the need to revisit the hole and potentially alter its position. There were two issues with the new angle-head unit, it could not use the flood coolant system so the holes were drilled “dry”, and potentially the drill could heat-up, picking-up fine particles of swarf, and cut over-sized holes. There was some evidence that this may have happened, with the diameter of the holes in some rows increasing, as shown in Figure 32, pp 93.

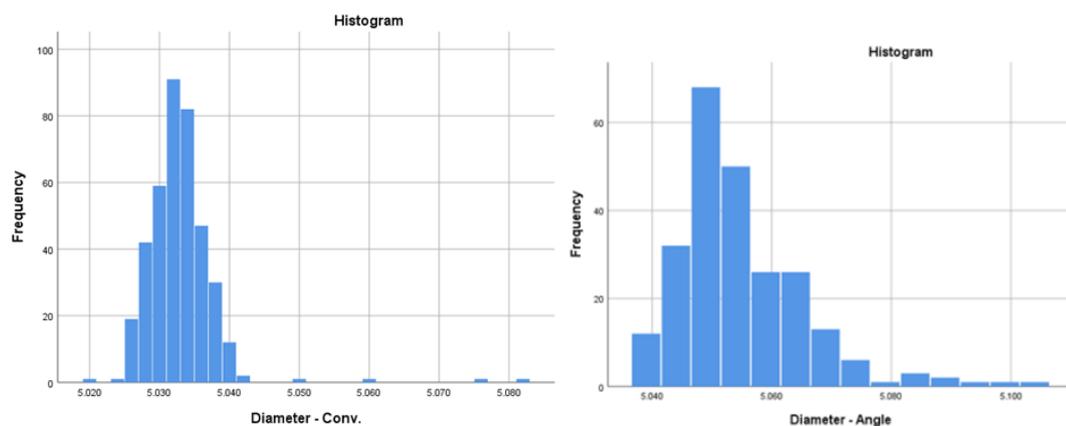


Figure 32: Histograms - Conventional (l) and Angle-head (r)

The left-hand histogram for the conventionally drilled holes shows no skewness, while the right-hand histogram for the angle-head drilled holes has a significant skewness to the right; an indication of some holes being over-sized.

The second issue was to overall length when the drill had been inserted in the head, it was greater than the width of some of the smaller pockets so they could not be drilled by the machine tool; this is an example of manufacturing process limitation which needs to be added to the TSM.

There are benefits to drilling all the fastener holes during detail manufacture rather than on assembly; the time taken is significantly less, an estimated twenty-to-one reduction can be achieved, the general quality is improved, and it enables P2P assembly.

Based upon the simulations, which do not necessarily include acceleration and deceleration, it was estimated that all the holes required to assemble IAAD 1B could

be drilled in under 35 minutes. There is also no allowance for load and unload, changing of the drill assembly, or use of the probe to align the part program to the fixture.

The final trial during part manufacture was to release them on the fixture then apply a light force to determine if the application of “light-hand pressure” would remove any distortion. The tests showed the parts could be drawn flat by applying a torque of less than 3Nm to a bolt; the significance of this value is it is less than that which would be applied to the fasteners in the structure. Therefore the fasteners would not be over-torqued to draw the parts together.

5.4.5 IAAD 1B Predictive Shims

The frame probing data-set, the most significant data-set as it would determine the size of the gap and subsequently the thickness of the shims, was collected during their manufacture and subsequently manipulated at BAE using metrology software (BuildIt). The data had been collected relative to the machining fixture’s datum, and was re-aligned to the part datum using the 3-2-1 method. The same features were used to hold the part during assembly and to align it to the aircraft datum. The data-set consisted of groups of six-points per interface, and were its actual location points relative to the part-datum. The data was imported to CATIA, and a simple rule-set was applied to determine the thinnest shim and the number of AM layers required to print it. A check was then performed to confirm that the distance between the upper surface of the shim model and the largest of the six-points was less than the sealant allowance. It was in all cases therefore no part-layers of shim would be required. At a part-to-part level a joint would not be expected to taper more than the sealant allowance, however the skin to structure gap is very likely to taper, as well as be stepped between one part and another.

The AM process chosen, from those available in-house, was Selective Laser Sintering (SLS), the machine used was an EOS P770, and the material was PA 2241 FR, a flame-resistant polyamide (PA 12) material. The factory settings were to lay layers of 0.15mm, so a calibration exercise was performed to lay a series of sprues, of 1, 2, 3 and 4 layers, representing the range of likely shims, see Figure 34, pp 96.

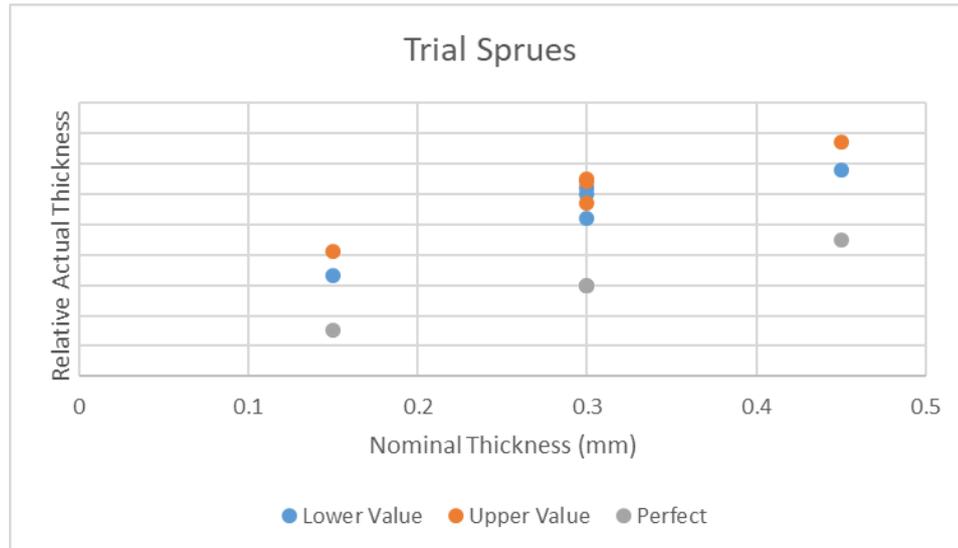


Figure 33: Trial Sprue Plot

The thickness of the shims produced were measured and recorded, the upper and lower values of which have been plotted, see Figure 33, pp 95.

The equation of the best-fit line is:

$$Y = 1.1667 X + 0.2$$

This indicates there is an initial off-set of 0.2mm, and each layer is on average 0.175mm⁶ thick.

⁶ Each layer is nominally 0.150 mm, the gradient is 1.1667, therefore each layer, on average, is $0.15 * 1.1667 = 0.175$ mm thick.

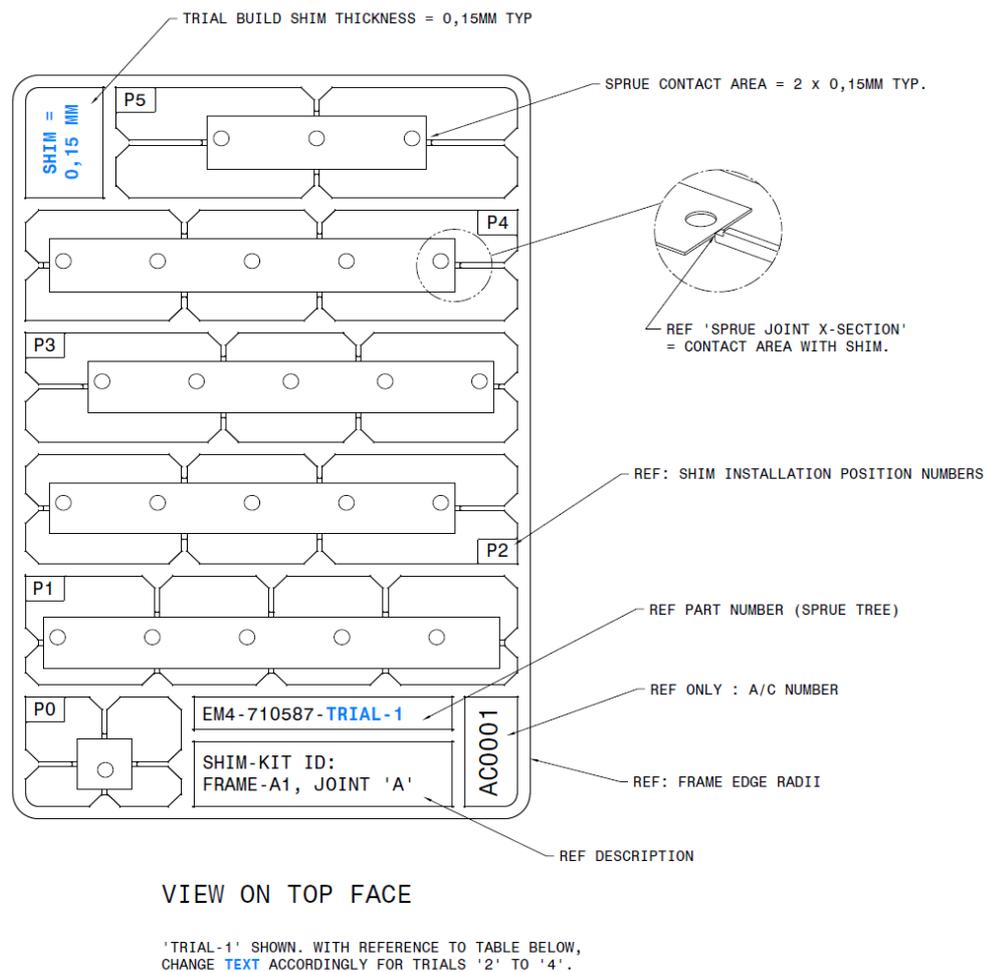


Figure 34: Example of Trial Sprue

The conclusion was the AM process was too inaccurate to warrant proceeding, and the factory settings could not be adjusted by the user.

Internal discussions then determined there was a knowledge gap covering materials suitable for shimming and their processing; it also transpired there was no Cardinal Points Specification for shim materials i.e. a statement of their performance requirements. This has led to a trade study being undertaken by Exeter University's Centre for Additive Layer Manufacture (CALM), to identify candidate materials and methods of processing them, as shown in Figure 22, pp 73, the flow down of projects.

The decision was also made to continue and assemble IAAD 1B but use toolmakers plastic shim as per IAAD in place of AM shims. So enabling some conclusions

about the use of predictive shimming and one-way assembly to be drawn, and thus determine if they are viable processes to use on the next generation of air vehicle (Tempest).

5.5 Assembly

This sub-section discusses the assembly of IAAD at UoN, and the assembly of IAAD 1B at the AMRC in Sheffield.

5.5.1 IAAD

The primary aim of the IAAD project was to assemble the parts using robots to aircraft tolerances. This was undertaken, as previously mentioned, in partnership with University of Nottingham in their FA³D cell, see Figure 35, pp 97.



Figure 35: FA³D Cell Assembled for its Launch (source: UoN)

The FA³D cell contained three Kuka robots, one KR1000 Titan on a pedestal, and two KR270 R2700 floor mounted on plates which had been drilled to allow the robots to be repositioned in a 2m x 1m area; all used the Kuka KRC4 controller. The Titan robot's function in the cell was to lift and manipulate the frames, modules and the whole assembly, as well as diverter panel. The KR270 robots positioned the shear-webs, floors, and fixed-skins.

The KR270 robots had tool changers, made by Staubli, which allowed them to swap end effectors to hold different parts. The end effectors could be used by either robot due to the symmetry of the design. This was aided by the use of an AMF zero-point clamping system, in which the clamping element was universal and the pull-studs, could be swapped, enabling 3-2-1 locating of the part on an end effector; as per a traditional fixture.

The pull-studs are available in three types, zero-point (red), timing (blue), and undersize (green); as shown in Figure 36, pp 98.

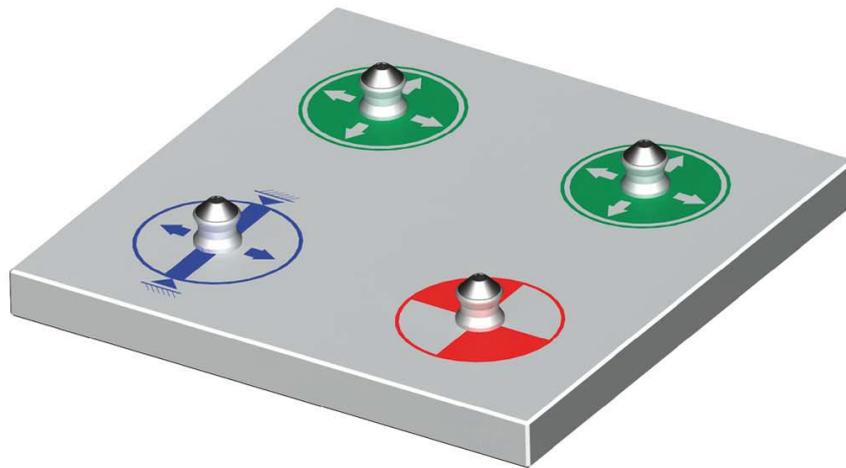


Figure 36: Classic Pull-Stud Arrangement (source: AMF)

Various dimensions of the clamping modules, $\text{Ø}62\text{mm}$ and 26mm , were conveyed to Design along with those of the pull-stud system, $\text{Ø}10\text{mm}$ and 2.5mm . This allowed the positions of the tooling holes and the thickness of the bases of the pockets to be set. The universality of the clamping modules allowed the same end-effector to be used for both left and right handed parts, where datum schemes are mirror images of each other.

The AMF clamping modules are normally mounted on a machine tool bed, using the T-slots to locate them. The proposal was to replace the machine tool bed with a modular end-effector system such as the SpiderGrip™ from DeStaCo. The principle of the system is very similar to that of modular tooling, which was described in Section 3.2 Assembly Fixture, pp 41.

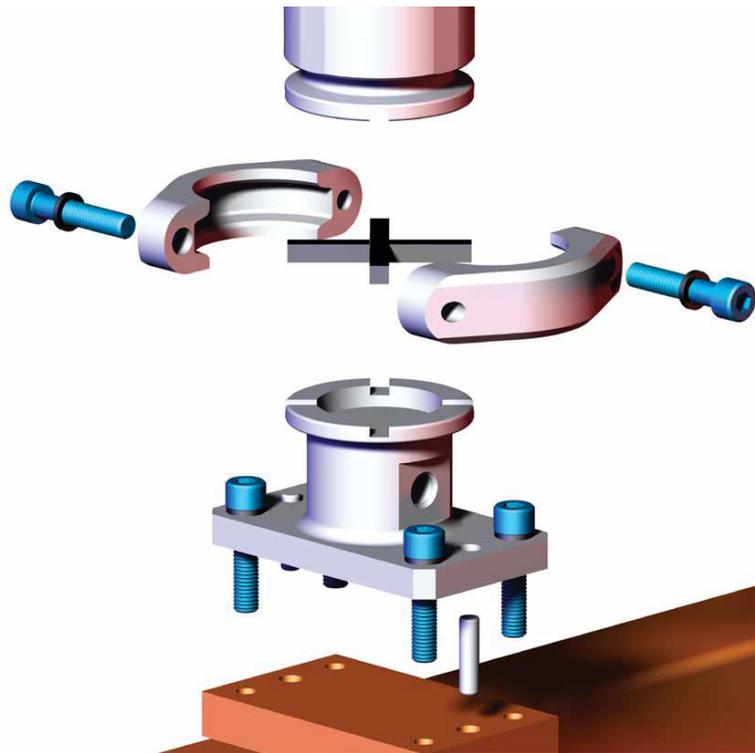


Figure 37: SpiderGrip™ End Effector System (source: DeStaCo)

The system, see Figure 37, pp 99, consists of a series of standard parts from which an end effector can be built. While the parts are high-quality when assembled they will not be accurate, which is inconsequential as only the end-feature or locator must be set, see Figure 38, pp 99. This is achieved using the same methodology as used on modular tooling; a metrology device and a CAD model set the end feature relative to a datum scheme such as the tool centre-point.

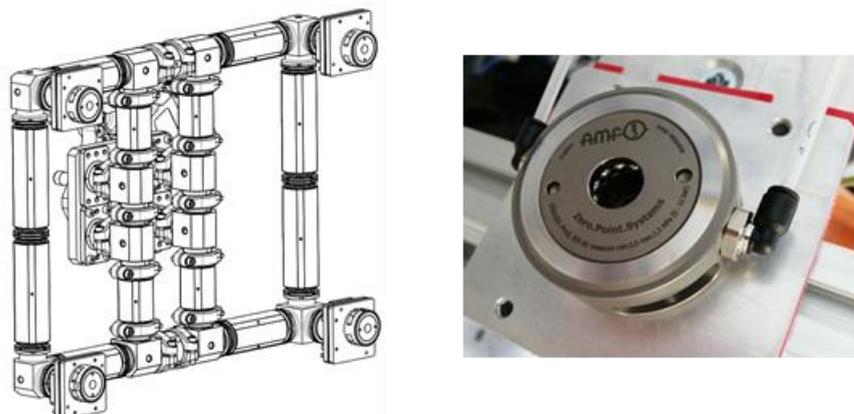


Figure 38: Examples, SpiderGrip End Effector and AMF Clamping Module (source: UoN)

Standard industrial robots are repeatable but not accurate, so to overcome this deficiency they can be coupled with a metrology system and using the process of assemble-measure-move or move-measure-correct can be accurately positioned to a reference frame. On the FA³D cell the Nikon K-CMM was used, but it equally could have been a laser tracker made by Leica or Faro. The cell has been described in parts 3.1, 4.1 and 4.2 by Drouot et al ((Drouot et al., 2018). The paper discusses the accuracy of the K-CMM using the example of a 2400 x 800 mm aircraft component. The absolute accuracy achieved was less than ± 0.10 mm, which is equivalent tooling tolerances. An estimate of the K-CMM average accuracy, from the data in the paper, is 0.033mm; these are the values given by the K-CMM and there is no evidence that they were verified using any of the other metrology systems available.

An ATS-Bus made the cell ready to explore the Internet of Things (IoT), Big Data, and Industry 4.0 (I4.0) within a reconfigurable manufacturing system. The top level scheme, Figure 39, shows the interconnection of the main items of hardware, and gives an indication of the data flow.

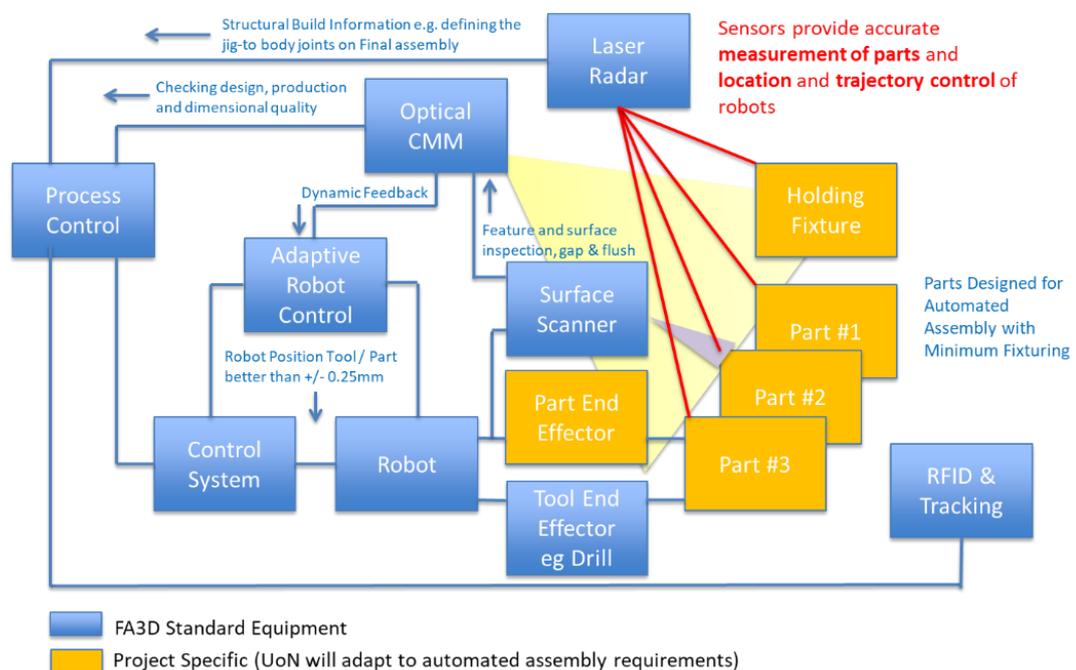


Figure 39: Top Level Schematic (source: UoN)

The assembly planning was defined in a series of five ASO (assembly sequence of operations) which gave the order the parts were installed. The first three sequences started and ended with the positioning of a frame, to create a module which was then customised to match the seams of the carbon skins. Between the frames the left and right hand sub-assemblies of two shear-webs and a floor were positioned by the two KR 270 robots. Once each module was temporarily assembled, the fastener holes were enlarged to full diameter and the permanent fasteners installed; this provided stability to the module, allowing it to be released from the zero-point clamps and set aside.

This demonstrated one-way assembly; drilling and fastening without needing to disassemble to deburr. The joints were “dry”, no sealant was used, to allow the structure to be disassembled in the future if required. This showed that robotic assembly will need a predictive drilling process, either one-way assembly or determinate assembly, or interchangeability, with no deburring otherwise disassembling the structure will be complex.

The planning was manually generated and at very high-level. A framework such as that in Figure 40, pp 101, (Maropoulos et al., 2008) is required, and it needs to be linked to the whole digital enterprise, or model-based enterprise (MBE); this will be discussed in more detail in the next chapter.

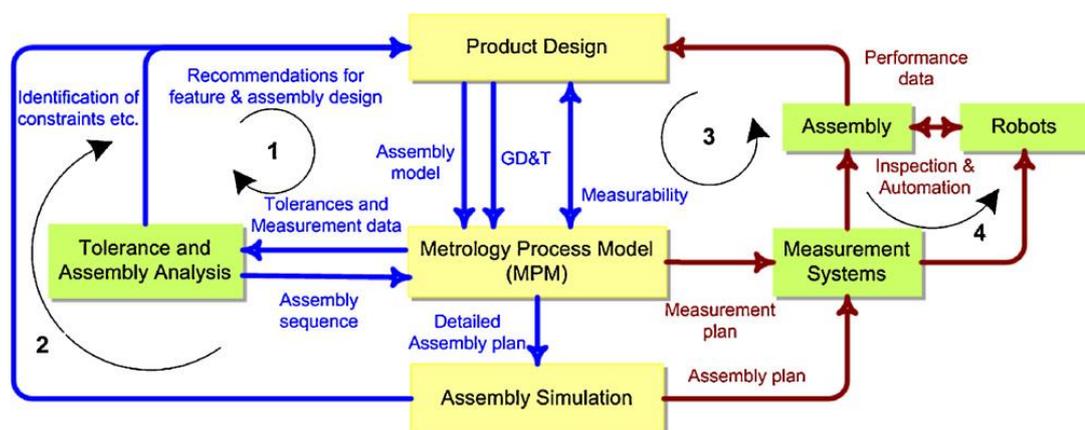


Figure 40: Theoretical Framework for Integrating Measurement with Assembly Planning (source: (Maropoulos et al., 2008))

With the distance between frames a constant 800 mm, the position of the common parts relative to the datum face of the forward frame of a module was the same; so it was possible, due to the design, to create a common working zone in which to

assemble all three modules and customise them. This would not be practical in a traditional fixture.

The use of two opposing robots, each doing the same task but on the opposite sub-assembly, meant just four base programs were required, then by changing the reference frame of each robot the opposite hand was installed.

The constant spacing of frames along a fuselage is not uncommon, therefore the concept of a common working zone is a practical proposition; and as per the angle-head drilling this has been captured in advice to Design [function] for inclusion in the TSM.

A common working zone can be used to assemble modules, but to assemble the modules into a product, particularly the installation and drilling of any fixed skins, it is probable that both the assembly and the robots will need to be repositioned to have access to all holes. This was demonstrated on IAAD with the installation of the outboard shear-webs and fixed-skins. In their original positions either the KR270s could not reach to install the outboard shear-webs and were too close to install the fixed-skins, hence the cell needed reconfiguring; both KR270 robots were moved, and the assembly was rotated 90-degrees.

Reconfiguration is very likely to be a requirement of any automated cell to assembly the next generation of air vehicle; plates were used in this use case, and they are a very practical, low cost solution. Other solutions are available, including flexible floors and mobile platforms, these will be discussed in the following chapter.

Between the extremes of a fully automated cell and a purely manual cell there exists a version which can be run in three modes, automated, manual and collaborative. In the collaborative work space the robots may be automated as per IAAD, or they may provide some location and an operator manually loads the parts, or as per LOCOMACHS see Section 4.5.4.3, pp 56, where the operator works with a collaborative robot.

A fuller account of the IAAD project was provided in an internal report, the main body of which was the final report for the IAAD project as a whole. It was prefaced by a discussion, conclusions and recommendations in the context of this research, (Carberry, (2017)) .

5.5.2 IAAD 1B - Initial Plan

The initial plan was to explore predictive shimming by installing AM shims based upon measurements taken during the manufacture of the parts, and assemble the parts using the FA³D cell at Nottingham, as per IAAD. As discussed previously, in Section 5.4.5 Predictive Shimming, pp 94, the AM shims were not manufactured. The plan had also scoped out to reuse the FA3D cell at Nottingham but with one significant change. The large end effector used by the Titan robot would be replaced with two smaller end effectors, one for each Kuka KR270, and running the robots in a cooperative mode (Master and Slave), see Figure 41, pp 103. The aim was to explore the options of using multiple smaller robots in place of one large robot. Unfortunately the FA³D cell was not available, hence an alternative plan was needed.

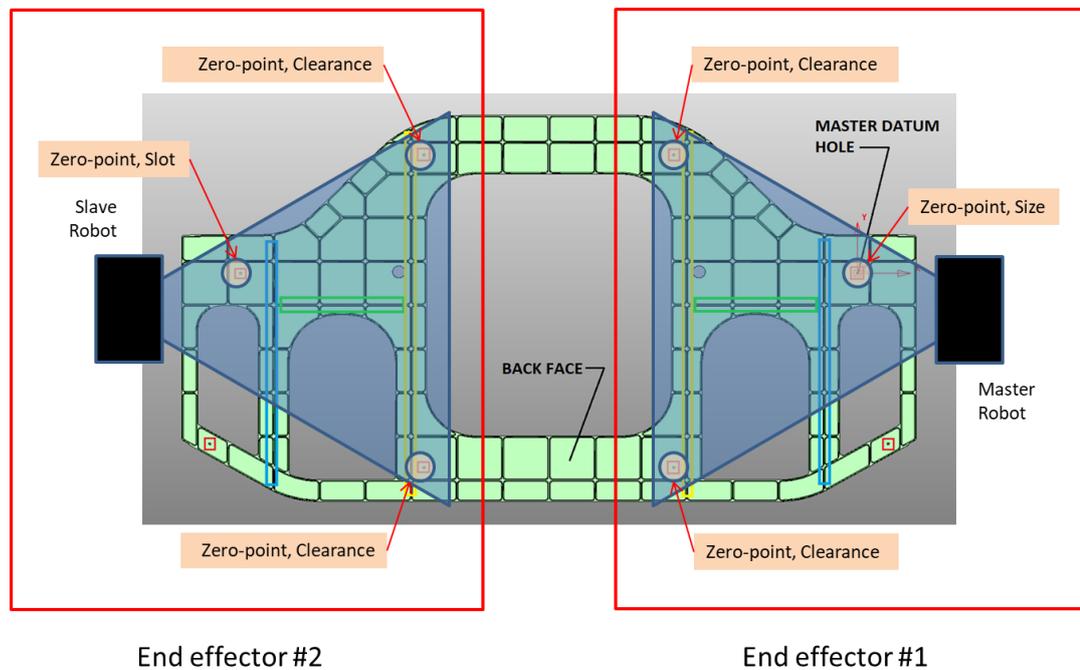


Figure 41: Co-operative Robots, Twin End Effectors

5.5.3 IAAD 1B - Alternative Plan

The delay in completing IAAD had an impact on the start date of IAAD 1B, there were then budget constraints and the cell was not available for the whole period. The project was de-scoped. In place of the robots, end effectors and a metrology system, a simple fixture of eight-posts was proposed. Similar fixtures had been used by both Taranis and nEUROn, two flying UAV demonstrators made by the UK and

French consortiums respectively. The scope of work was modified to include, the design and manufacture of a fixture, the assembly of the parts using toolmakers shim, and undertake a further comparative trial; assembling the frames to nominal values versus best-fit values, with the aim of understanding the impact on the variation in the thickness of the shims required. Nottingham could not undertake this new work, so the AMRC was contacted.

5.5.4 IAAD 1B - Eight-post Fixture

A package of work was scoped out with the AMRC and BAE designing the fixture; BAE's involvement was to ensure, if required, the fixture could be repatriated and installed without major design changes. The fixture was installed on a reconfigurable floor, see Figure 42, pp 104, which gave an insight into some of the practical issues that might be associated with the use of the Hexapods, as described previously in Chapter 4, pp 56.

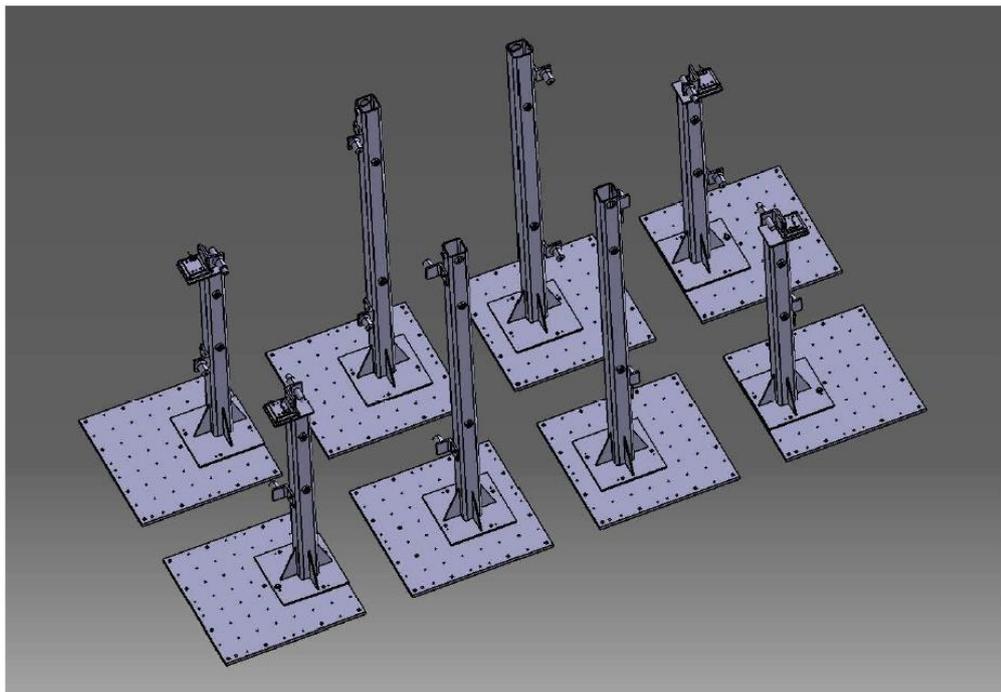


Figure 42: CAD Rendering of Full Fixture on Reconfigurable Floor

5.5.5 IAAD 1B - Predictive Shimming

The thickness of the shims was calculated from the probing data collected during the manufacture of the parts. The actual gap size was calculated from the data, and then converted into shim “packs” that were assembled from sheets of toolmaker plastic shim, which comes in a range of thicknesses from 0.025mm to 1.250mm. A laser

profiling machine, driven by CAD geometry, was used to cut each shim from a sheet; it is a very quick process and may have practical use if the shim is supplied line-side in sheet form.

5.5.6 IAAD 1B - The Assembly

With the shim attached to the shear-webs and floors, the frames were loaded into the fixture, see Figure 43, pp 105. It was at this point that it was discovered the assembly had been unwittingly designed to be assembled in one particular way only.

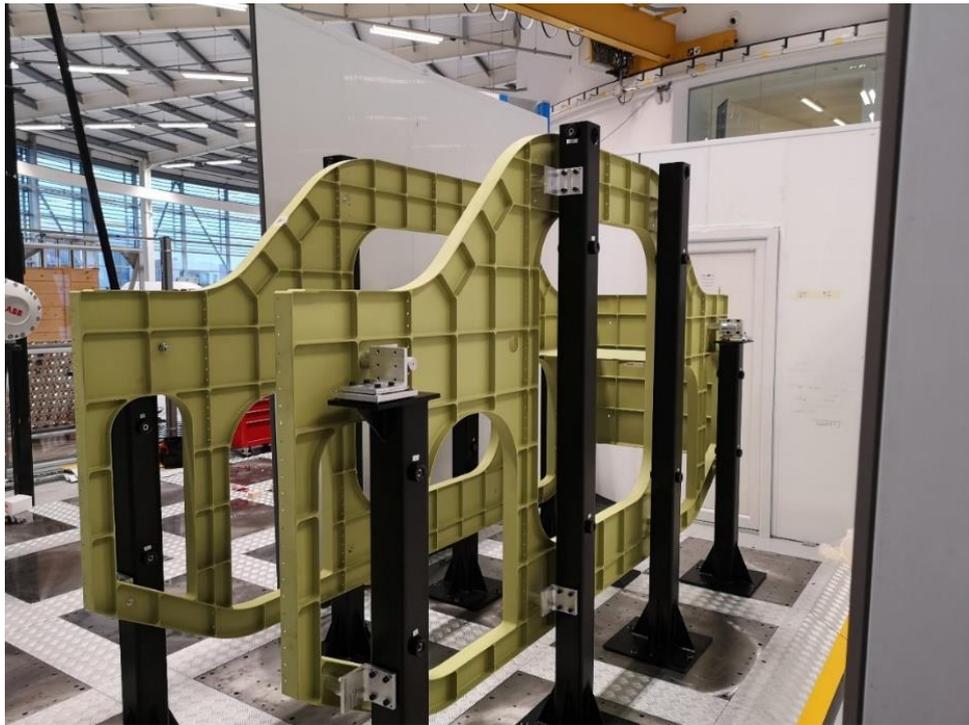


Figure 43: Initial Installation of Fixture

The design had been based upon an assembly methodology that involved attaching the shear-webs and floors to the first frame, then locating the closing frame; critically that involved a translation of approximately 25mm. It was discovered when the frames are in their final positions, that neither of the shear-webs could be installed, the pockets were too narrow to allow them to be rotated into position, which would be normal practice in a traditional assembly fixture.

The solution was to add 20mm of movement to the aft frame pick-ups; allowing the shear-webs and floors to be installed before the aft frame was advanced to its final position.

5.5.7 IAAD 1B - Inspection

With the parts assembled the upper flanges of structure were inspected, as per Figure 44 pp106. The graphic shows they were all within tolerance ($\pm 0.200\text{mm}$). This demonstrated the parts could be assembled using the predictive shimming method to a tolerance which would allow the skin to be installed with a shim, the thickness of which could be determined using virtual assembly.

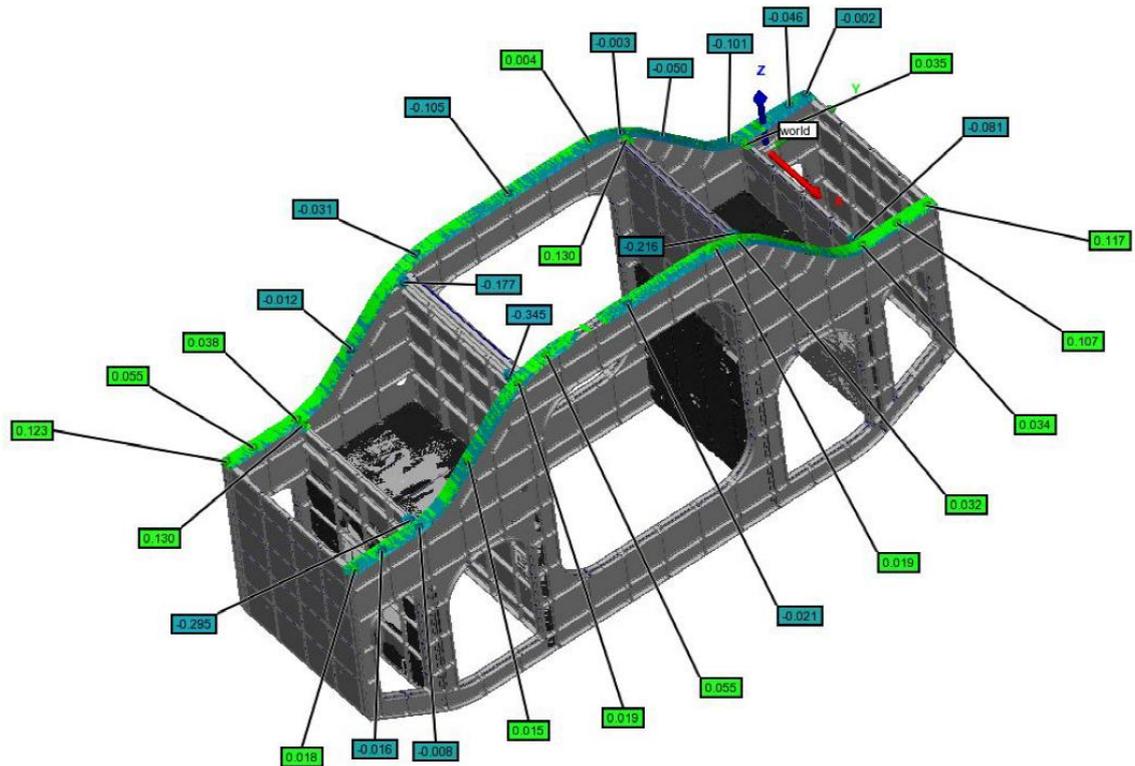


Figure 44: IML Scan of Assembled Structure in Fixture

Verifying the location of the internal parts was more difficult; the original assembly planning had each part installed and inspected before the next part was added. The revised planning partly installed all the parts before joining them to the aft frame. This made inspection of the datum faces close to the joints almost impossible, and the data that was collected was of limited use.

The steps between the frames and shear-webs were also analysed, as there is a maximum allowable by Design. The results showed the aft steps were greater than the forward steps; which is likely to be due to the method of assembly. The forward joint was created first, so there would be a moment due to the weight of the part, causing it to rotate or pivot on the fasteners.

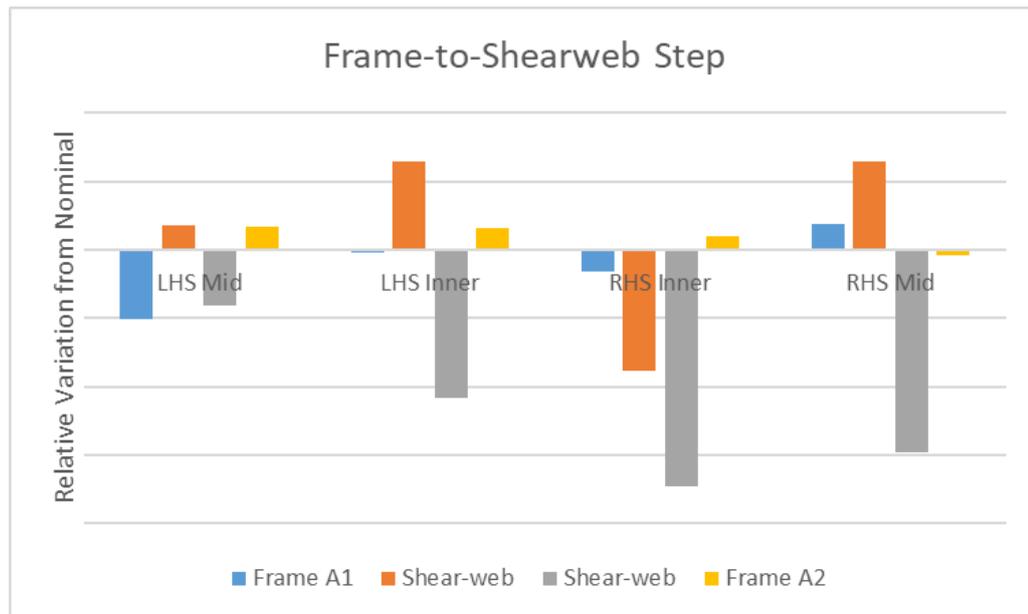


Figure 45: IML Steps

The rotation is evident from the values for the second shear-web (grey), see Figure 45, pp 107, they are all negative; ranging from -0.10mm to -0.35mm, while the aft frame was less than ± 0.050 mm.

As the data for the shim packs was being collated it was also analysed for the first of the comparative trials described as a planar best-fit; the aim was to determine if the frames could be repositioned horizontally (+/- Y) to equalise the average size of the shims. The average gap sizes for both frame, left and right hand sides, are shown in Table 5, pp 107. The differences between LHS and RHS were both less than the thinnest layer of shim available, and as the gaps are opposite each other in the design no adjustment was made.

Frame	LHS (mm)	RHS (mm)
No. 1	0.247	0.252
No. 2	0.233	0.231

Table 5: Average Frame to Shear-web Gaps

5.5.8 IAAD 1B - Part-to-Part Assembly

The second aspect of the IAAD 1B project was to predrill all the fastener holes full diameter at the part manufacturing stage. As discussed earlier the holes were drilled using conventional and angle-head methods Section 5.4.1, pp 85, the conventional holes were on average 5.032mm in diameter and the angle-head holes 5.055mm.

The hole-to-hole alignment, in a Digital Twin / Virtual Assembly context, was assessed. It involved two data-sets, the diameter of the holes as measured using the Bowers Gauge and the centres of the holes extracted from laser-scanner data. The laser-scanner data needed importing into PolyWorks software to extract the centre-point data. It was done as a proof-of-concept, so only the LHS inboard shear-web was assessed, see Figure 46, pp 108, and the calculations indicated that 50 percent of holes aligned sufficiently to allow a nominal diameter fastener to be inserted.

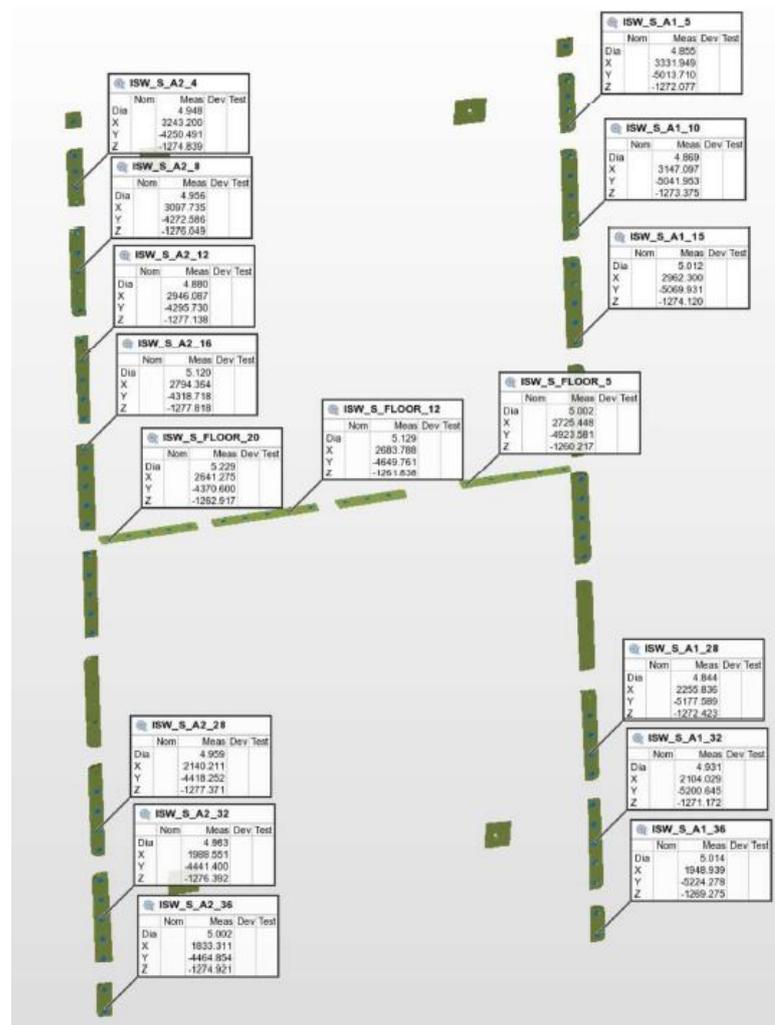


Figure 46: LHS Inboard Shear-web Hole Centre in PolyWorks

Of interest is the comparison of a hole diameter as measured using the Bower gauge (the current production method) and as calculated by PolyWorks (the proposed method for the Digital Twin). For both methods of drilling the calculated diameter was smaller than the measured holes, the conventional holes were on-average 0.088 mm smaller and the angle-head holes were on-average 0.247 mm smaller. Using the scan data the angle-head holes were on-average 0.137 mm smaller than the conventional holes, which is the reverse of Bower gauge data, that had the conventional holes on-average 0.023 mm smaller than the angle-head holes.

The scan data was collected in one-pass of the hand-held laser, which for the conventional holes was approximately normal to the surface, but for the angle-head holes it was at 45-degrees to access the vertical faces of the flanges. This meant the number of data-points around the edge of a hole were not equally spaced which skews the result of the best-fit algorithm used. The conclusion was that further work will be necessary to determine the orientation of the scanner and the number of passes required when scanning the parts to create the Digital Twin and undertake virtual assembly. The use of a vision system and a machine-learning algorithm would be an alternative to the Bowers gauge, potentially speeding up and automating the inspection process, then ultimately combined with the scan-data, allowing virtual assembly and in a Big-Data context providing insight.

The assembly methodology required the top-most fastener in each row to be installed first. A check of these holes showed they were all in tolerance, and there was no significant difference in the diameter of the forward holes and the aft holes. The conventionally drilled holes were all drilled in the shear-webs, and their average was the same as that of the whole data-set. The angle-head holes were all drilled in the frames, and their average was less than that of the whole data-set, at 5.048mm. This is consistent with the top-most holes being drilled first in a row, and the diameters increasing due to pick-up. The parts were fastened together with Cleco temporary fasteners, with a specific instruction to align the blade vertically.

The conclusion that can be drawn is, all fastener holes could be drilled during part manufacture then fastened into an assembled structure, with some development of the angle-head drilling process.

The fixture and parts were repatriated to BAE's Warton site and installed in the Factory of the Future, where it will be used to demonstrate predictive AM shimming.

5.6 Conclusions and Next Steps

The following section identifies the achievements of the whole project.

The assembly of IAAD at Nottingham using the FA³D cell demonstrated that metrology guided robots can be used to assemble a section of an airframe to current tolerances. While the assembly of IAAD 1B at the AMRC demonstrated predictive shimming combined with part-to-part ICY/DA drilling enables a Meccano™ assemble. The former would primarily reduce the non-recurring costs of a project, while the latter would reduce the main recurring cost of touch-labour, as well as impacting the non-recurring cost of jigs.

With some further developments such as improving angle-head drilling and collection of on-machine data, the Meccano™ assembly method can be improved and made more robust.

In the spectrum of part-to-part assembly, ICY/DA and one-way drilling were both used successfully, and only MADA needs to be trialled to have data on all the fixtureless MAA processes.

There are a significant number of recommendations that need including in the Technical Standards Manual; these have been collated into a set of "rules" see Appendix B: Design Rules for Technical Standards Manual, pp 167.

There needs to be some basic research and development of additive manufacturing to determine a suitable material and method of applying it.

Not inconsequential are the benefits of a strengthened partnership with University of Nottingham, and the continued contact with the AMRC and the catapult network, as well as demonstrating to the company's CTO that the Manufacturing Technology department can deliver the disruptive technology he seeks for new products.

The above points will be discussed in more detail in the next chapter on Innovation and it will be shown how they provide direction to the engineering objectives and

the business need, ultimately answering the research question which was the catalyst for this Eng.D study.

6 Contribution to Innovation

6.1 Introduction

Below, in Figure 31, pp 112, is a visual representation of the projects and their phases, starting with the Samlesbury Robot Project and concluding with the Factory of the Future, that this research has contributed to (purple) and discussed in unpublished, internal reports (green, yellow, orange, red), see key for a guide.

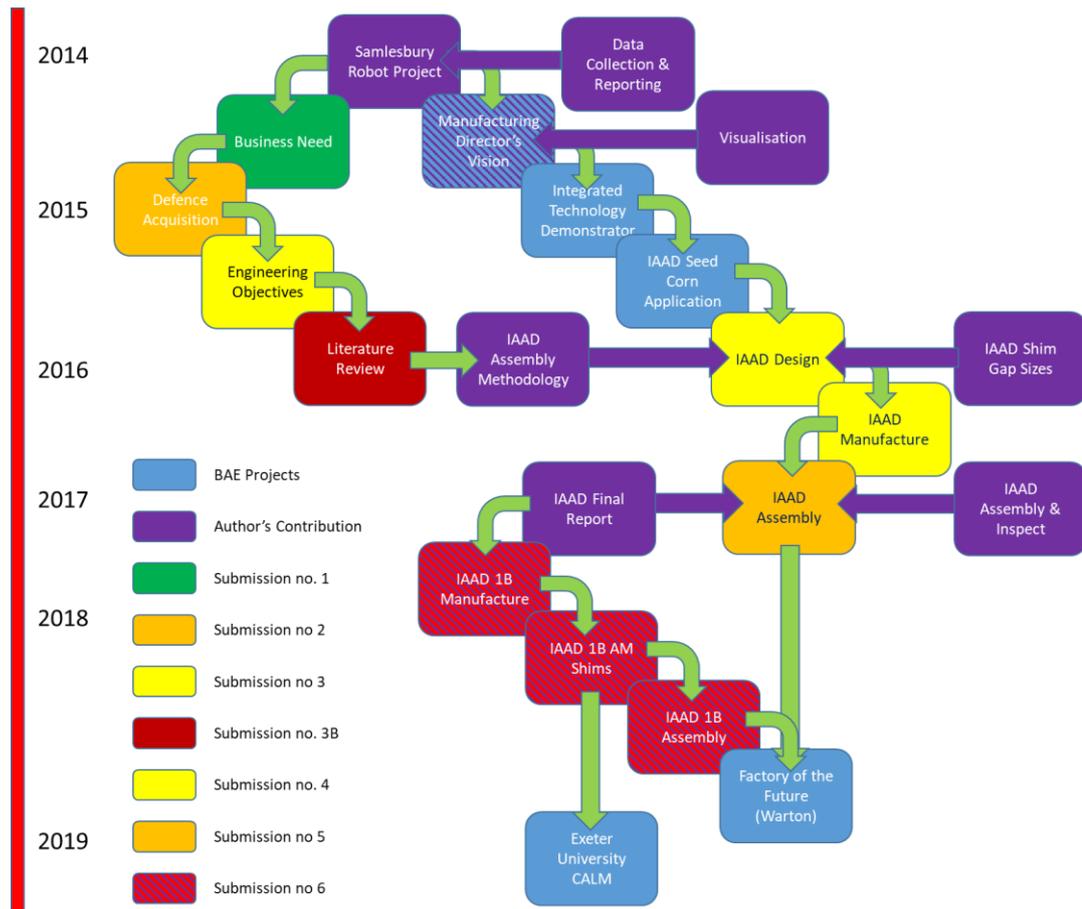


Figure 47: Contributions to the Programme

6.2 Programme Innovation

Throughout this report a number of key areas of innovation have been discussed and to which this research has contributed to significantly, they include;

- The employment of standard industrial robots coupled with COTS items such as tool changers, modular end effector systems and zero-point clamping systems, controlled in a closed-loop by an external metrology system to replace traditional monolithic assembly fixtures. This detailed understanding extends beyond previous studies which focused on systems based upon affordable reconfigurable tooling. This addresses an engineering objective that was defined at the start of this project.
- The manufacture of bespoke shims using an additive manufacturing process from data collected during the manufacture of the parts. This was supported by the design of gaps between the parts which were the sum of the capability of the manufacturing process and coatings applied to the interfaces. This eliminates the need for the craft-based process previously used that involved the non-value added work of installing and removing a part numerous times. This addresses part of the second engineering objective, also defined at the start of this project, with a complete process reversal from fettling to shimming.
- The drilling of all sub-structure part-to-part fastener holes during the manufacture of the parts using machine tools. They can be drilled either full or pre-ream diameter, enabling the parts to be assembled rather than fitted, eliminating working in confined spaces with restricted access and the use of additional tooling. This addresses part of the second engineering objective, also defined at the start of this project, concerning drilling on assembly with expensive machine tools.

Combined these innovations create a method of assembling the next generation of air vehicle using automation.

6.3 Patents

This research has resulted in four patent applications being made by BAE Systems, see Table 5, pp 114, and as detailed in Appendix C, pp 169.

BAE Reference	Title of the Invention
XA5296	METHOD AND APPARATUS FOR PRODUCING COMPONENT PARTS OF AIRCRAFT AIRFRAMES
XA5297	METHOD AND APPARATUS FOR PRODUCING AT LEAST PART OF AN AIRCRAFT AIRFRAME
XA5317	METHOD AND APPARATUS FOR ASSEMBLING AIRCRAFT AIRFRAMES
XA5318	METHOD AND APPARATUS FOR PRODUCING SHIMS

Table 6: Patent Applications Linked To This Research

Application XA5296 refers to the process of machining a part to CAD nominal data, measuring key surface features, and creating from that data a digital-twin (DT) of the part; the DT is then used to produce the CNC program to drill the fastener holes. The manufacture of the parts for IAAD 1B, as described in Section 5.4.4, pp 89, formed the basis of this application, (Coulier et al., 2019).

Application XA5297 describes the process of using the DT of two parts, virtually assembling them and creating a CAD representation of any void between them; the CAD model is then used in the additive manufacture of a bespoke shim that fits between the parts. The predictive manufacture of shims for IAAD 1B, as described in Section 5.4.5, pp 94, was the basis of this application, (Carberry and Fletcher, 2019).

Application XA5317 describes how CAD models of the parts, fixtures, end effectors and robots are used to align one or more pairs of holes so that fasteners can be installed. The assembly process described in Section 5.5.1, pp 97, was the basis for this application, (Carberry and Coulier, 2019).

The final application, XA5318, is a method of producing AM shims to be fitted between the skin and the assembled structure. From a DT of both the skin and the assembled structure a digital model is constructed of a shim to substantially fill the

gap. The model is then used by an AM process to manufacture a shim, which is typically of double curvature and less than 1mm thick. The process was undertaken as part of the assembly of the diverter panel on the IAAD assembly, (Sharples et al., 2019).

Collectively they protect the Intellectual Property (IP) generated by this research, and by registering these patents BAE Systems can reduce the level of Corporation tax paid on profits (Government, 2007) generated from their use.

6.4 The Business Context

In a business context uncertainty over requirements has historically driven both the supplier and customer to be optimistic about cost, time, and capability. This has resulted in projects being delivered late and over-budget, (Gray, 2009: pp 16). The defence budget, set at 2 percent of GDP, is under tremendous pressure particularly over the next decade due to this optimism. Therefore starting a new project, such as Tempest, will be harder; hence new business models are being explored with countries like Italy and Sweden. Team Tempest, a separate but related entity, comprises industry and the RAF working together to provide the technologies, knowledge, skills and expertise to develop a Next Generation Combat Air System.

Tempest will be the first aircraft to follow the CADMID life-cycle process from the start. The process has critical assessment points at the initial gate at the end of the concept phase and the main gate at the end of the assessment phase. The technology should be TRL 3 at the end of the assessment phase, and then TRL 7 by the “point of the main investment decision”, (National Audit Office, 2013: pp 7). If the main investment decision is the placement of the production contract, then the trigger for it will be first-flight of the first development aircraft. Boeing’s TX-Trainer solution of using a Model-Based Enterprise (MBE) has been disruptive, not least because their bid was half the Department of Defence’s (DoD) budget. Boeing, with their partner Saab, claimed to have created a prototype that was almost EMD⁷ ready, a fact supported by the EMD flight trials starting 10 months after contract award, compared to the 5-years it took JSF, see Figure 48, pp 116.

⁷ EMD is the Engineering and Manufacturing Development phase in US programme, following contract award, equivalent to the Demonstration phase of CADMID on a UK programme.

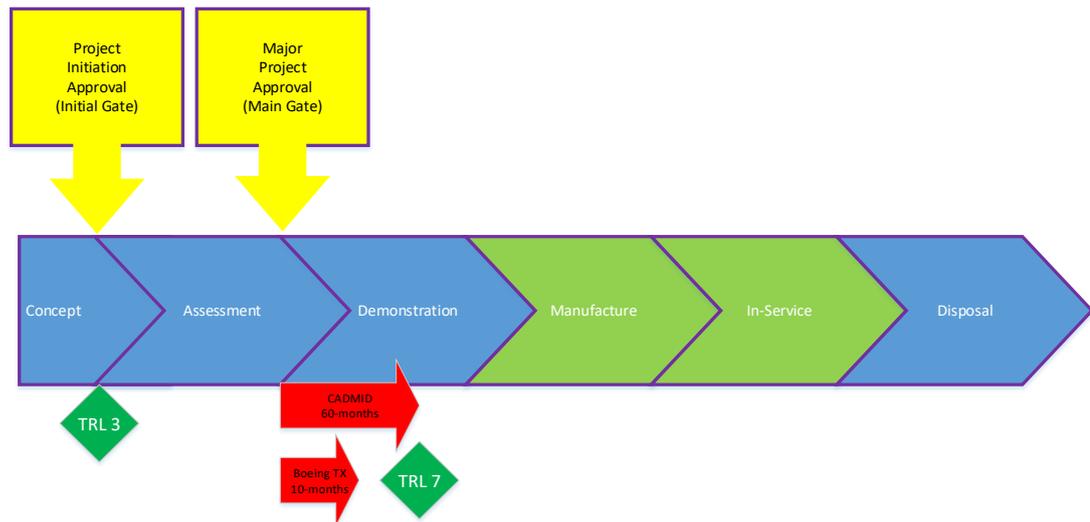


Figure 48: Achieving TRL 7 – Typhoon versus TX-Trainer

If correct this will considerably shorten the time-to-market by negating the re-design that typically occurs after contract award, and place pressure on engineering and manufacturing to achieve TRL 7 in a compressed timescale. This could be achieved by demonstrating robotic assembly on a prototype or demonstrator aircraft, which unlike the traditional approach, would allow the processes and resources to be reused; thereby creating a product with a batch-size of one. The learning will also be transferable enabling the project to start further down the learning curve, shortening the time-to-market.

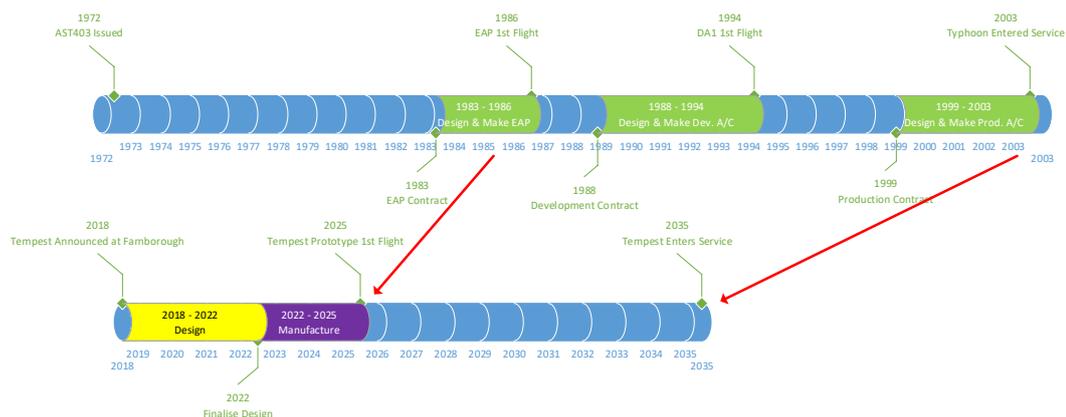


Figure 49: Compressed Timescales – Typhoon & Tempest Comparison

The high level aims for Tempest include being 50 percent cheaper and having a 50 percent faster lead-time (BAE Systems plc, 2019), as represented in Figure 49, pp 116. Neither of these values can be qualified, but Boeing's success on TX using

model-based systems suggests they are not unrealistic targets, which would ease pressure on the defence budget, and support an in-service date of 2035; based on Typhoon taking 30-years.

Currently, there is only limited publically available information (Nathan, 2018);

The plan is to finalise design in the early 2020s, produce a flyable prototype by 2025 and have the aircraft entering service by about 2035.

Which has been represented in Figure 49, pp 116.

If MBE is used, as per Boeing TX, and the flyable prototype is closer to a development standard of aircraft, then what took 8-years on the Typhoon programme might be compressed into maybe as little as 1-year on the Tempest programme, see Figure 50, pp 117. A chronology of the TX-Programme has been included in Appendix D, pp 173.

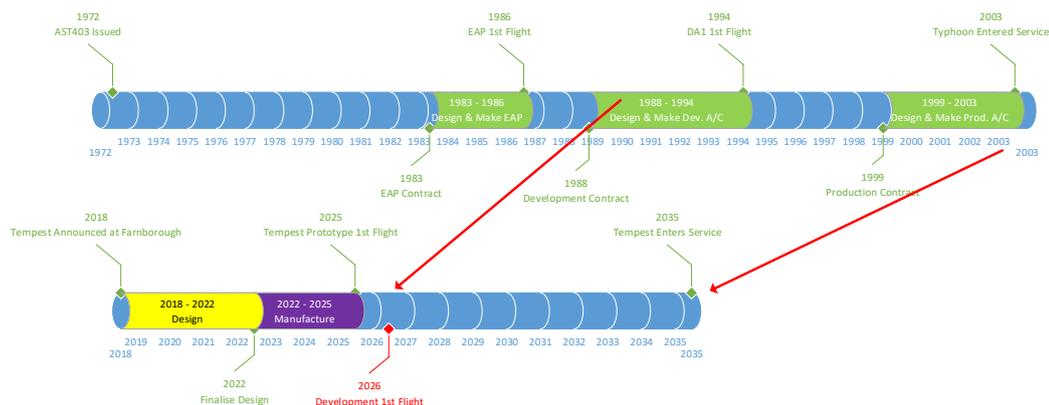


Figure 50: TX Philosophy applied to Typhoon

6.5 Application to Other Sectors

The most common sector that aerospace is compared with is the automotive sector. The overall assembly processes are similar; fabricated and machined parts are assembled into either an airframe or body-shell (body-in-white, BIW) using welded-steel fixtures to locate the parts. A significant difference is that in automotive the whole body-shell is completed on a single line, while in aerospace wings, fins, and sections of the fuselage are often assembled in different factories, and frequently now in different countries as part of off-set work agreements, before being aligned

on a final assembly line, see Chapter 3: Current Best Practises, pp 41. In automotive, manufacturers prescribe the assembly system, identical assembly lines exist in different countries, whereas in aerospace its either make-to-print or it is at the supplier's discretion what processes and methods are used; the former is typically off-set work, while the latter is part of a joint venture.

Interchangeability is another key difference between the aerospace and automotive industries. In automotive it is a given that everything is interchangeable and designed to be assembled, which is a necessity to ensure that parts and sub-assemblies can be installed in less than 3-minutes; in aerospace it is a classification of fit, requiring cross-matched tooling and operators with craft-skills. Both the pressed steel body-shell parts and the machined aluminium airframe components are made to high tolerances but distort when unrestrained due to stresses induced during their manufacture. The body-shell parts are clamped and spot-welded together, while the airframe components are located and the gaps are checked, with only light-hand pressure allowed before drilling, deburring, and fastening the parts together; finding an alternative for this process is the major part of this research.

While both aerospace and automotive use assembly lines to build the airframe or body-shell (BIW), the most striking difference is the volumes that rolls off them. Typhoon at its peak was 60 aircraft per year (Stevenson, 2017) and F-35 at its peak is “one-per-day”, but these peaks are only for short periods, less than 5-years. In contrast, Boeing's 737 assembly line reached 57 aircraft per month in 2019 or 684 per year (Brady, 1999), however this dwarfed by an automotive assembly line, BMW's Mini assembly line at Oxford produces 1000 per day (Floyd, 2018). Military fast-jets are produced in significantly lower volumes than civil jets, and minute quantities compared to most automotive brands, even super-cars are produced in greater volumes – Ferrari 8,000 per year, and Rolls Royce 4,500 per year. A further difference between the two types of assembly line is that automotive lines get reconfigured for new models, while aerospace assembly lines make only one model.

Another significant difference is change, the automotive industry tends to work on a 4-year cycle for major changes, with mid-life up-dates every 2-years. Aerospace programmes last many decades, Typhoon for example has used the same facilities

for the last 30-years, while Boeing has been assembling 737's at Renton, since moving there in 1969, over 50-years.

A further difference is automotive use of the platform design, which enables a group such as VW to build different models on the same assembly line. The concept is about sharing and reducing production costs by increasing volumes, which is beneficial across all market segments. It also reduces the costs associated with the development of products. Outwardly distinct models are based on the same platform, see Figure 51, pp 119. The platform design idea is not about sharing sheet metal parts but design considerations such as, how the engine is mounted, what the crash structure is at the front end, which brake callipers are used, and where does the instrument cluster and radio come from.



Figure 51: Modular Vehicle Platform (Source: WhichCar)

A platform allows an automotive group to assemble different marques, on different assembly lines in different countries, for local markets; for example VW group based the Volkswagen Polo and SEAT Ibiza on the same platform. Both sectors use lean-assembly lines, parts delivered line-side, just-in-time.

While the aerospace and automotive sectors have many common traits, as described, the volumes made on automotive assembly line make the technology proposed by

this research unlikely to impact the current methods; it may however impact sub-assemblies such as doors, bonnets, and tail-gates, where the flexibility would allow one cell to assemble a range or set of sub-assemblies.

BAE Systems is seeking a more agile, reconfigurable manufacturing capability for the expected low-volumes, in aerospace terms, and the variable build rates of future fast-jets. It is looking to achieve this by building its future factories around advanced manufacturing technologies like additive technologies, robot assisted assembly, intelligent logistics and autonomous robotics, with the aim of boosting productivity. This is consistent with the definition of agile manufacturing (Yusuf et al., 1999: pp 36);

“A manufacturing system with extraordinary capabilities to meet the rapidly changing needs of the marketplace. A system that shifts quickly (speed and responsiveness) among product models or between product lines (flexibility), ideally in real-time response to customer demand (customer needs and wants)”

The agile manufacturing model presented, see Figure 52, pp 120, encompasses the concept of reconfiguration, as well as the Virtual Enterprise which can be interpreted as the Model Based Enterprise, and the Knowledge-driven Enterprise which is Big-Data, AI and machine-learning, and Industry 4.0.

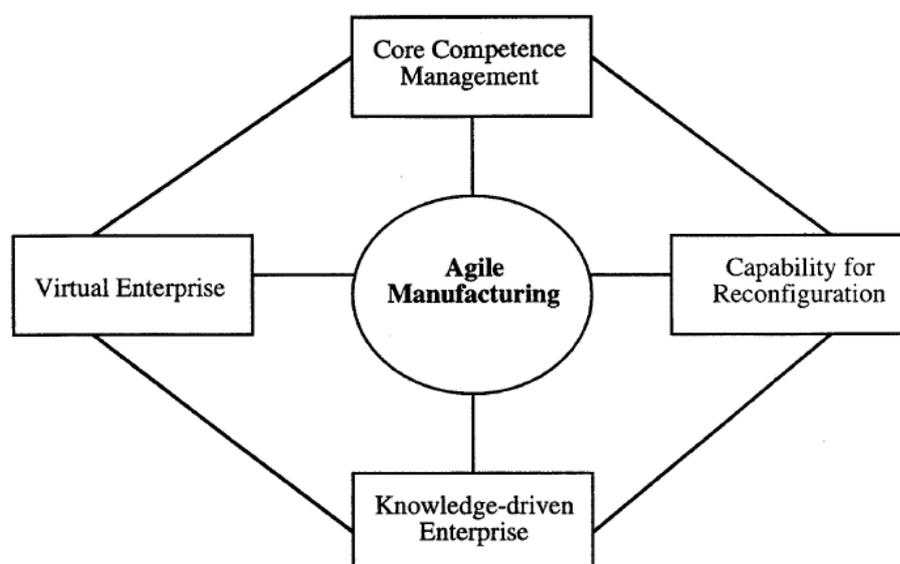


Figure 52: The Core Competencies of Agile (source: Yusuf et al)

The agile, reconfigurable paradigm is an evolutionary approach rather than disruptive or game-changing. In the context of assembling the next generation of air vehicle the business requires a viable method, which can be developed over the next five to ten years, as the product matures. A big challenge identified during this research is how an agile, reconfigurable manufacturing system evolves, and in the context of airframe assembly, how an up-dated or new process is approved for use; while not explored by this research, one solution may be through the use of Digital Twins and virtual assembly, which are discussed in Chapter 6 – Contribution to Innovation, pp 132.

There are examples of robots and reconfigurable fixtures being developed for the automotive assembly. In one example Gough-Stewart platforms are positioned using an ABB robot (Bem et al., 2017), and in a second a flexible fixture motivated by the marine organism, *O. vulgaris*, the common octopus, assembles sheet metal parts (Arzanpour et al., 2006). The former achieved results similar to those reported in Section 4.5.4.2 - An Automated Flexible Tooling Framework (AFT), pp 56, while the later proved the concept by confirming the reconfigurable fixture was sufficiently flexible in its design to be able to grasp a set of four sheet metal parts. A key distinction between these studies and this research is their working volumes; these studies focused on volumes less than 1m^3 while this research was on a volume of 18m^3 , and the impact of metrology is more significant.

An alternative sector which may benefit from this research is air-taxis; there are already many companies world-wide exploring the opportunity they present for local air-travel. Conceptually many are autonomous electric vehicles with multiple rotors to provide vertical take-off and landing (eTVOL), see Figure 53, pp 122.



Figure 53: Bell's Nexus air taxi vehicle, developed for Uber. (Source: Bell)

While airliners connect cities on a global scale, air-taxis are targeted to connect local communities affordably; estimates for a 20-mile/15-minute flight are \$40.

The air-taxis are similar in size and complexity to the front fuselage of a fast-jet, and many employ the carry-through design of wing used on trainer-jets; which would make the technologies and methods of assembly proposed by this research a viable alternative to a traditional fixture. The agile, reconfigurable nature of this research means one facility could manufacture a range of air-taxis from the same basic equipment, and it further presents the opportunity to customise individual vehicles or manufacture small volumes. While the concept of a platform-design is not practical on fast-jets, it may be used by air-taxi manufacturers to build a range of vehicles; lowering overall cost by not producing unique designs for each model.

6.6 Focus of this research

Unfortunately radical is not always practical, and this research needed to be useful to the company. The innovation shown needed to be useable, and based upon experience rather than be speculative and maybe ill-informed.

Aerospace has its fair-share of automation “white-elephants”; and BAE management until recently were sceptical of the robots, preferring the robust, solid engineering of

machine-tools instead. The introduction of the automated countersinking cell with its frames and modular pick-up, see Figure 54, pp 123, changed that perception. The correct application and development, with management buy-in at every stage, ensured a robust system was delivered that has the highest Overall Equipment Effectiveness (OEE) of any piece of equipment on-site.



Figure 54: Automated Countersinking (source: BAE Systems)

The business need for this research is affordability, both recurring and non-recurring costs, and one of the engineering objectives is to eliminate or reduce the reliance on machine tools in assembly. The internal view is the machine tools used are too expensive (purchase, installation, and infra-structure), and their large-scale foundations make the assembly environment inflexible to change. The machines tended to be of bespoke design, and volumes are low; however there are other machine tool manufacturers who now produce similar machine tools, which are as accurate and have reduced installation costs, so there may be an opportunity in the future to explore the machine tool market.

In conclusion, this research needed to be useful to the company, and support the strategic direction it is pursuing.

6.7 International Placement at KU Leuven, Belgium

The international placement provided informed thinking giving specific insight into introducing robot assisted assembly to an existing facility, and a broader in-sight

into the adoption of fundamental research. It provided an alternative perspective, on general robotic research and research in non-UK establishments.

An aim of the placement, beyond expanding the research academic network, was to understand the research associated with the task of introducing a robot-based system into a production line quickly, so reconfiguring the workspace where humans and robots could be collaborating to assemble a product. Supplementary to this was the impact that the broad and innovative research at KU Leuven had on local technology companies.

KU Leuven had participated in the EU FP7 funded Factory-In-A-Day (FiaD), (Filos, 2017: pp 20). This project showed a simple robotic pick and place system could be introduced onto a production line in a day, if the implementation was split into two half-days with approximately a month for design, manufacture, and integration of the system between them.

The implication of this finding on this research is the need to consider how a future assembly cell would be reconfigured, quickly and safely. While the IAAD cell at University of Nottingham was reconfigured to assemble the product, it was a demonstration akin to Reconfigurable Manufacturing System (RMS), (Koren et al., 1999), where the reconfiguration was built-in through the utilisation of reconfigurable hardware and software, and was consistent with agent-based research at Nottingham into Plug and Produce assembly platforms, (Antzoulatos et al., 2014).

In the Factory-of-the-Future, where new and evolving processes are envisaged for a batch size of 1, the FiaD research showed there will need to be period of time before the installation when the requirements are defined, followed by a longer period when the hardware is assembled and the software programmed. Key to these phases on FiaD was the use a workplace simulation tool that showed the client the proposed solution and got their buy-in. In this research it is envisaged a Digital Twin, virtual assembly and VR/AR will perform as similar function.

If the resources are limited or there are safety concerns, the current cell might need to be taken out of production while the new robot is installed. The problem may be further exacerbated if the hardware is already in use and not available until the cell is taken-down; delay in production would be of concern to production management as stop-time will impact the Overall Equipment Efficiency (OEE), a measure of

productivity, making the technology un-popular. An example is the Fuselage Automated Upright Build (FAUB)⁸, see Figure 55, pp 125, installed in 2015 to automatically assemble Boeing's 777 fuselage, teething problems that caused poor performance were not resolved, and in 2019 it was abandoned in favour of proven semi-automatic methods.



Figure 55: Fuselage Assembly Upright Build (FAUB) (source: Boeing)

FiaD also highlight other barriers to getting this research adopted. It showed there is a lack of systems integrators prepared to undertake these more challenge low-volume systems, and it was proposed new business models may need to considered, for example where the robot is loaned such as in fruit-picking where the needs are seasonally.

To facilitate quick change-over, lean techniques such as Single-Minute Exchange of Dies (SMED) can be used, as well as appropriate hardware like quick-changers and zero-point clamps, as well as common service interfaces.

BAE Systems had links with tech-companies in the Leuven area prior to the placement. BAES uses additive manufacturing (AM) software called MAGICS from Materialise in its AM centre, and CAMIO software from Nikon Metrology on its CMMs. Both Materialise and Nikon Metrology have strong links with the PMA (Production engineering, Machine design and Automation) department at KU Leuven, where the placement took place. Both companies were spin-offs in 1990's

⁸ Boeing (2017). Boeing: A Futuristic View Of The 777 Fuselage Build. [online] Available at: <http://www.boeing.com/features/2014/07/bca-777-fuselage-07-14-14.page> [Accessed 9 November 2017].

from research done at the university, and senior management in both companies are alumni of KU Leuven too.

Products from these companies are closely linked to this research. Materialise who design and manufacture AM parts, built AM machines, provide AM software used by BAE. Nikon Metrology, had acquired Metris, who in turn had acquired Krypton Electronic Engineering in 2005 for its portable optical CMM hardware known as K-CMM, provided the metrology hardware used by University of Nottingham to accurately position the robots to assemble IAAD.

Both companies were familiar with working with aerospace companies, and understood the tight tolerances and requirement to measure everything.

From interviews with both companies the following insights were obtained.

Materialise highlighted that their machines currently were not capable of producing thin-layers (< 50 microns) from which shims could be manufactured, and did not have a suitable material; in addition all parts needed hand-finishing.

They were currently manufacturing C-class parts for the aerospace industry, so had an appreciation of the strict controls required.

Nikon on the other hand had a product, CAMIO, which could be used immediately with some customisation, but its use was limited to CMMs. For robotic applications its FOCUS product appeared more appropriate, with its capable of taking input from a wide range of measurement equipment. This research was seeking to understand if a single software solution existed for all metrology equipment used in aerospace.

Nikon's interest this niche market of metrology guided robots ceased in 2018, approximately the same time as the placement, with the sale of the rights to K-CMM product and the adaptive robot control (ARC) software to True Position Robotics Ltd. based in Nottingham.

The act of taking fundamental research and commercialising it was of interest to this research, particularly with reference to the UK's high value manufacturing catapult, and its purpose of bridging the "gap" between academia and industry.

KU Leuven appears, based upon the presence of Materialise, Nikon, LayerWise (now part of 3D Systems) and others, to be successful at commercialising fundamental research without the obvious presence of a Catapult or Fraunhofer. The key points determined from discussions with academics in KU Leuven, who had set-up spin-off companies, were:

- Identifying a problem that needs fixing, for which no solution exists.
- Setting up the company in the locality of the university.
- Maintaining the link with the academic origins of the company.
- Doing it, and accept some ventures will fail, but it will be obvious in 5-years.
- Not necessarily knowing which market segment is the immediate target.

It was evident from informal discussions with the academics that there is a general entrepreneurial mind-set in the university. They recognise, through their links with industry through organisations such Flanders Make, that there are industrial applications for the fundamental research they are developing. There is support through the university to develop business and financial plans, explain how to manage IP, and help attract investors. They recognise to remain ahead at a technology level, the new company still needs to invest time and money on internal R&D, and it is important to maintain links and collaborate with the university; one-way this is done is through an Innovation and Incubation Centre in close proximity to the university.

6.8 Future Innovations

A number of ideas evolved throughout the course of this project which provided scope for further research and development; these are briefly described below.

6.8.1 Short-term Future Research and Development

The following short-term research activities have been undertaken, following completion of the IAAD1B project.

Suitable Shim Material: The trial identified that there was no suitable AM material from which to manufacture the shims. It also highlighted the lack of a Cardinal Points Specification for shim in general, without which a suitable material cannot be

identified. A specification was created, allowing candidate materials with the correct properties to be identified.

Method of manufacture: While the method of manufacture is intrinsically linked to the material, the products have specific needs such as their overall accuracy and the thickness of a single layer, which are much tighter than current capabilities. Discussions with machine manufacturers and bureaus identified potential machines and methods; which will help identify the road-map to a production solution and inform any make versus buy decision.

Data collection methods: The methods of collecting part data were reviewed, and the parts were scanned using a GOM ATOS III system (GOM - a ZEISS Company, 2020). The data was then processed through Polyworks (metrology software) and Solidworks (CAD software), to create a .STL file for each shim. These files were then passed to suppliers for manufacture.

Part-to-Part: The fixture was repatriated to BAE's Factory of the Future, and installed with the aim of fitting shims to certain joints to validate the process.

6.8.2 Long-term Future Research and Development

The following longer-term activities will be investigated in support of the Factory of the Future in general.

Data Storage and Analysis: Collecting, storing and analysing the data to manufacture the shim would be a first phase. The shim models can then be imported into the digital twin of the assembly, and collectively analysed, the findings of which would be fed back to Design [department].

Skin-to-Structure: The shims between the skin and structure are potentially thicker, longer, and curved, as well as possibly tapered. The data storage and analysis needs to be revised.

Part-to-Part with No Shim: The structural gaps between the parts are generally less than 0.50mm. A study should to be undertaken to determine if they are required.

Angle-head Drilling: The process of angle-head drilling requires further investigation if assembly rather than fitting is to occur; assuming cutter pick-up is a solvable problem. The size of the head with cutter and the setting needs defining in

the tooling standards, so pockets can be designed to accommodate them; as well as spindle speed, feed-rate, drill diameter and the process such as the direction hole patterns are drilled in, all need recording.

Shim Application to Skin: An alternative to manufacturing a shim would be to apply the shim material directly to the inner surface of the skin. This will involve combining some of the above studies with the creation of a method of applying the material in a controlled manner.

6.8.3 Factory of the Future

The factory of the future, in an aerospace context, will be a paradigm shift from the modern assembly hall of today. It will not be like current factories. It will be agile, reconfigurable, scalable, elastic, reproducible, and will evolve over time.

They are defined in an aerospace context as;

- Agile – reacting to the customer requirements.
- Reconfigurable - designed from the outset with the ability to change its geometric set-up
- Scalable – adjustment in response to market demand changes (Putnik et al., 2013)
- Elastic – the ability to flex an amount without change
- Reproducible – can be recreated, both locally and globally
- Evolvable – the focus is on adaptation through the capture of emergent properties (Onori et al., 2006)

The concept of the Factory of the Future satisfies the Tempest aims, see Figure 2, pp 6, which are to be capable, upgradable and affordable.

The following concepts will be part of the factory of the future and are discussed in more detail below; this is about where BAE needs to be and not necessarily about where it currently is.

The factory of the future, in the context of airframe assembly, will be based on the use of measurement assisted assembly (MAA). Standard industrial robots guided by metrology will replace traditional assembly fixtures, and be aided by metrology enhanced tooling for assembly (META) techniques such as using motorised

Flexapod, see Figure 56, pp 130. The same robots can then be repurposed to undertake another of the basic processes such as drilling, fastening and sealing; rather than doing just one task as they do in most industries.



Figure 56: Robotic Assembly Fixtures, Factory of the Future (source: BAE Systems)

Cobots will work alongside operators assisting them in a range of tasks e.g. installing fasteners. They can operate as a guide to the operator, for example, inserting fasteners in a defined sequence that was predetermined off-line, and connected to the smart-tooling that the operator uses acknowledging successful installation.



Figure 57: Mobile Metrology, Factory of the Future (source: BAE Systems)

Ubiquitous metrology, ranging from handheld gauges to laser radar, will be able to gather data seamlessly, in manual and automatic modes, see Figure 57, pp 130. Locally analysed, using Edge Computing, the data can be packaged into product and

process data-sets, and where necessary propose adjustments such as the alignment of the next part or compensation for temperature changes. The data can then be uploaded to the cloud for further analysis to provide an insight to the assembly environment, occurring at level C4 – Cognition Level, see Figure 67, pp 141, as defined by Lee, (Lee et al., 2015).

Traditionally robots are static either on assembly lines or in work cells; the proposal of moving robots is not new in aerospace, Dassault were drilling Rafale in the 1990s, (da Costa, 1996), but the concept of being able to design, assemble, use, then disassemble a cell for very low volume is, see Figure 58, pp 131.



Figure 58: Cell Reconfiguration, Factory of the Future (source: BAE Systems)

The reuse of the robots and associated equipment would reduce the non-recurring capital costs, as well as free up floor space and eliminate the overhead associated with storage of a fixture.

The Factory of the Future will be significantly more integrated with the supply base, both with internal and external parties. Using part data gathered during the manufacture of the parts and virtual assembly, assembly-related engineering decisions can be made through analysis, predictive models, visualisation, and presentation of data without physical representation, (Jayaram et al., 1997).



Figure 59: Virtual Assembly (source: BAE Systems)

Virtual assembly can be used in manufacturing for a number of tasks. It can eliminate non-conformance issues, create directions for sub-assembly operations, or adjust the manufacture of parts, etc. For example, it can be used in the manufacture of AM shims to fill the gaps using measurement data, see Figure 59, pp 132. The shims would then be manufactured through the supply chain or produced directly at line side printers on demand; this is a make versus buy decision, but who makes that decision is a high-level strategic decision.

The Factory of the Future will be driven from models by data, in a model-based enterprise (MBE), using model based definition (MBD) with process and manufacturing information (PMI). The benefits of MBE through the life-cycle has been tabulated, see Table 7, pp 133, by the Department of Defence (DoD), (Duncan, 2015). Key gains, in the context of this research include, virtually assembling multiple models, virtual manufacturing process evaluation, and fewer defects so less rework. For the Tempest programme it includes, faster and more thorough trade-space evaluation, better risk identification and mitigation, reduced non-recurring engineering, collaboration amongst stakeholders and data exchange, real-time configuration management, and faster time to market. Many of these benefits were realised by Boeing on the TX Trainer programme discussed earlier, and there is an US-based example of BAE Systems applying MBE to design, collaborate with the customer, and deliver mine-resistant, ambush-protected egress trainers to the (US) Army in approximately one-fifth of the time of a traditional engineering approach (4,000 hrs versus 23,000 hrs).

	Solutions Analysis	Technology Development	Engineering and Production	Support
DoD	Faster and more thorough trade space evaluation Improved cost modelling Virtual manufacturing feasibility assessment	Early assessment of producibility, maintainability sustainability, and affordability	Thorough assessment of producibility, maintainability sustainability, and affordability	Faster and less error-prone part sourcing/organic manufacturing Potential for more competition in bidding
OEM	Fast and more thorough trade space evaluation Improved cost modelling Virtual manufacturing feasibility assessment Virtual design review	Faster and more thorough risk identification and mitigation Virtual manufacturing processes evaluation	Reduction in the amount of nonrecurring engineering Virtual prototyping Fewer defects/less rework Faster time to market	Reduction in the amount of non-recurring engineering
Supplier		More thorough understanding of design intent in less time	Faster setup of manufacturing processes	Faster and less error-prone production
All	Collaboration among stakeholders and data exchange Real-time configuration management			

Table 7: MBE Improvements to Some Life-Cycle Activates (source:(Duncan, 2015))

MBD with PMI will allow design for manufacture and assembly, including choice of assembly methodology (part-2-part), (Maropoulos et al., 2014), tolerance analysis, and assembly simulation, (Maropoulos and Ceglarek, 2010), as shown in Figure 60, pp 134, of which there may be a number of iterations. The assembly simulation

would combine configuration layouts, CAD models, robot programs, and ergonomic avatars, to create the assembly planning and BOM to construct the cell or cells.

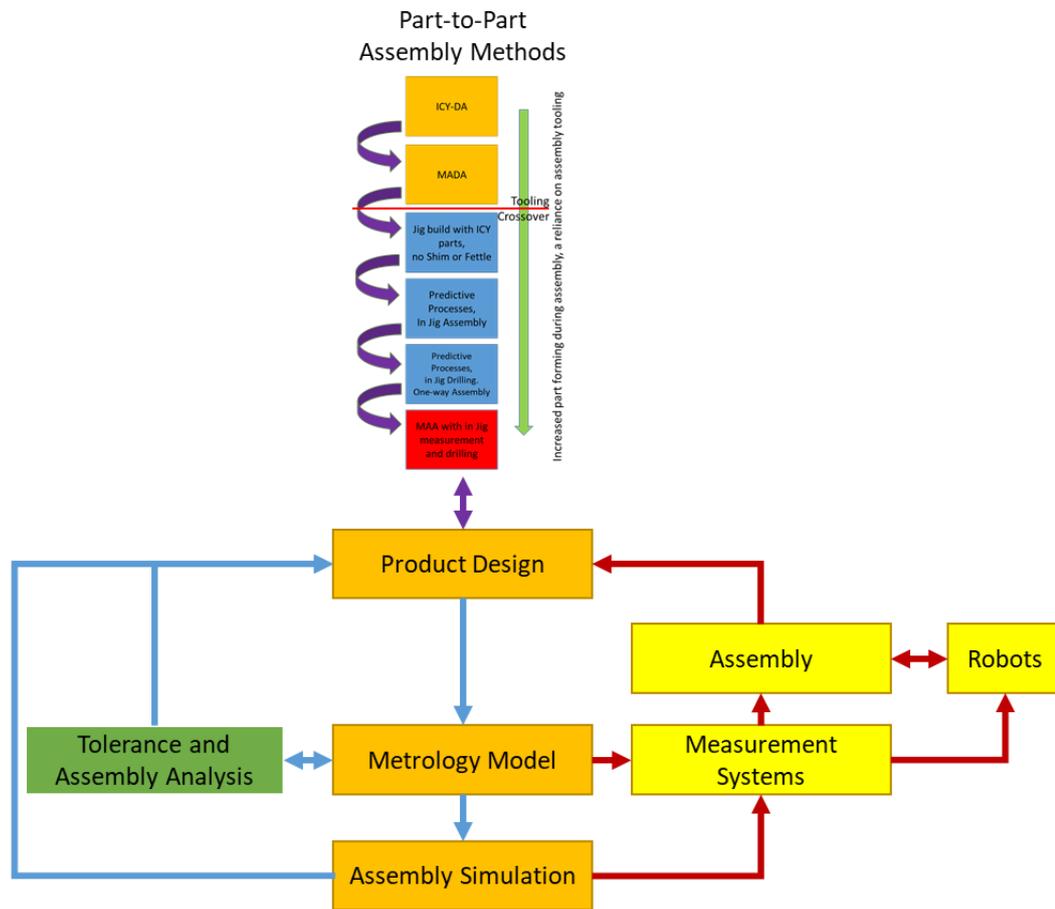


Figure 60: Overall View of Part-2-Part Assembly Methods, Integrating Measurement with Assembly Planning, and Measurement Assisted Assembly

Scheduling will be important for the disassembly of previous cells and assembly of new cells, to enable reuse of some of the parts. Cell construction will need to be aligned with part manufacture, whether internal or external, to deliver the right part in the right order using automated logistics, see Figure 61, pp 135; something that is currently achieved in the automotive industry (Dörmer et al., 2015).



Figure 61: Automated Logistic with Autonomous Mobile Robots

Data gathered during the assembly operations can be categorised into either product or process. The product data will help create a digital twin of the aircraft while the process data is analysed, to improve the process via a digital twin, and keep the design function informed of current capabilities. PMI data will be translated into operator instructions delivered directly to the operator and synchronised with smart tooling such that it prevents incorrect operation, see Figure 62, pp 135. This will benefit from the development of wearable technologies in sport and medical industries.



Figure 62: Digital Workbench, Factory of the Future (source: BAE Systems)

A development of wearable technologies, would enable the shims to have sensors added or embedded in them which would allow significantly more structural health monitoring; and may ultimately negate the need for test aircraft that are not always representative of the production aircraft, potentially enabling unique aircraft to be

manufactured and operated safely. This may require advances in quantum computing and DNA storage devices because of the amount of data involved.

6.8.4 Digital Twin

The Digital Twin was chosen as the emerging technology to investigate for a Technology Management module Post-Module Assessment (PMA) report. It showed, the concept of a Digital Twin was introduced in 2003 by Grieves as part of a Product Lifecycle Management (PLM) course at the University of Michigan, (Grieves, 2014), and it used a generic model proposed by the High Value Manufacturing Catapult (HVMC), see Figure 63, pp 136, (Hamer Craig et al., 2018).

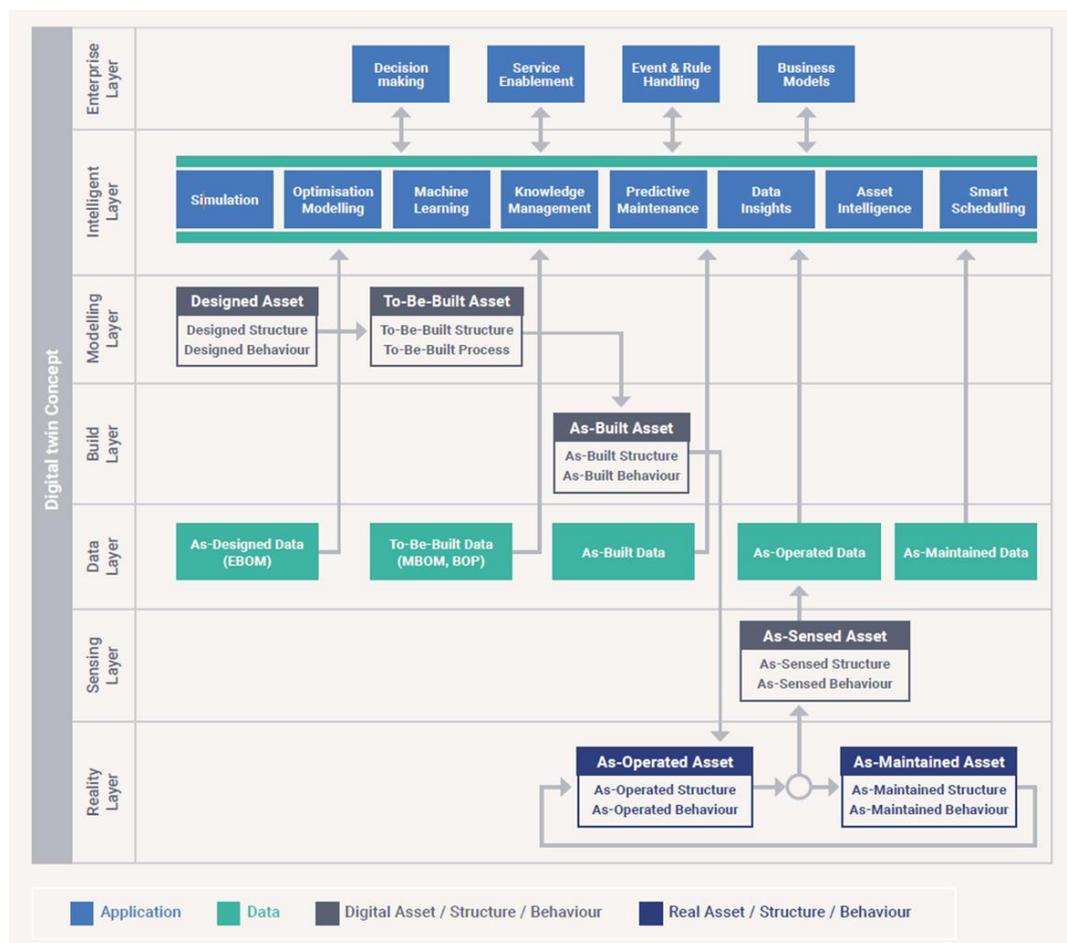


Figure 63: HVMC Digital Twin Architecture (source: HVMC)

The HVMC DT model defines layers and the interactions between them, which is akin to a reference architecture.

An alternative model has been created by Boeing, which couples the digital twin and the physical world in the context of a model-based enterprise, and has a relevant use-

case that demonstrated the same benefits this research seeks, namely faster time-to-market and an affordable product (commensurate with the customer's budget).

The model is a linking of Physical Systems (Design and Delivery) and Digital Twins (Modelling and Simulation) based on the systems engineering V-model, with horizontal connections from model-world to virtual-world and design-world to physical-world; as well as vertical connections from model to design, and physical to virtual, to convert needs into solutions. Boeing have termed it the model-based enterprise diamond or "Black Diamond", see Figure 64, pp 137.

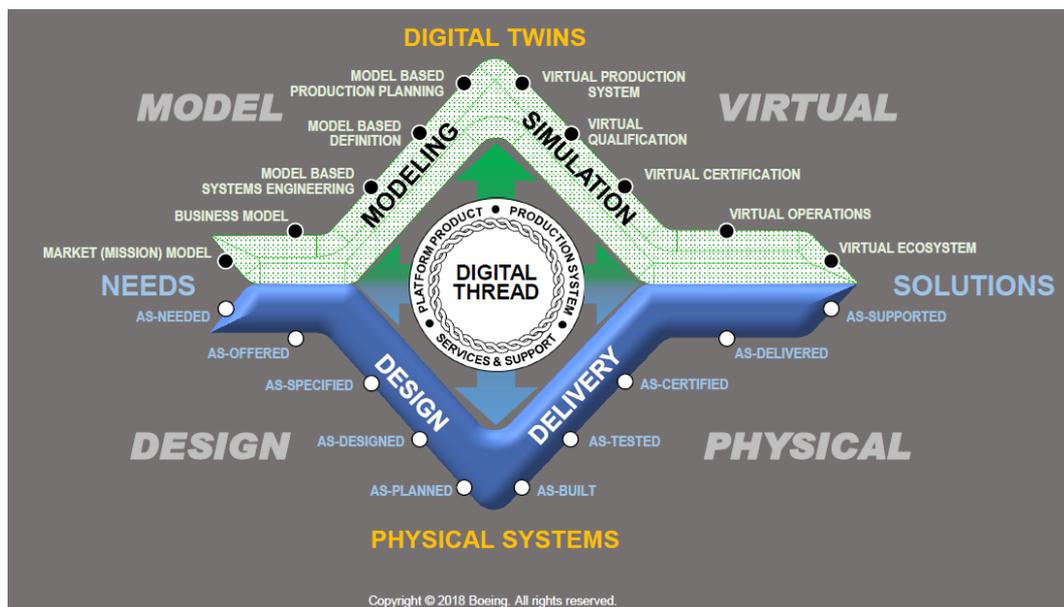


Figure 64: Boeing's Model-Based Enterprise Diamond (source: (Hatakeyama et al., 2018))

The MBE diamond was used by Boeing, and their partner Saab, on their TX-Trainer bid which was submitted at half the allotted DoD budget. A significant benefit of using this model was the two test aircraft produced were, in Boeing's opinion, engineering and manufacturing development (EMD) ready because the MBE had allowed them and their partners to keep evolving the prototype aircraft as the requirements changed or were clarified.

This is rare on fast-jet programmes, typically a re-design is required because the requirements have changed (see, Bankole, affordability), and this pushes back the in-service date.

Key for the next generation of air vehicle will be the investment in a model-based enterprise (MBE), and using model-based definitions (MBD) containing product and manufacturing information (PMI) to drive product lifecycle activities. It is important to make these changes now because typically once a programme is locked into a particular system changing it is very difficult to justify.

6.8.5 Physical World

The following section identifies six high-level concepts which will need to be considered in the context of creating the physical world of the Smart Factory, and enabling the digital twin in aerospace. The concepts are:

- Industry 4.0
- Industrial Internet of Things
- Cyber-Physical Systems
- Big Data
- Reference Architectures
- Reconfigurable Assembly Systems

For each concept there follows an explanation of what the concept is, and why it is relevant in the context of using automation to assemble Tempest.

6.8.5.1 Industry 4.0

What is the concept: A German Federal Ministry of Economic Affairs and Energy report from 2010 identified areas of research that had to be promoted to strengthen its position as a leading manufacturing power. Manufacturing technologies were seen as one of those enablers, and a study in 2014 by the Fraunhofer IAO titled “Industry 4.0 - economic potential for Germany” identified five fields which it considered in the study of the concept of I4.0, (Bauer et al., 2014). The fields were, Embedded Systems including intelligent objects and cyber-physical systems (CPS), Smart Factory, Robust Networks, Cloud Computing (flexible and distributed software), and IT-Security, see Figure 65, pp 139.

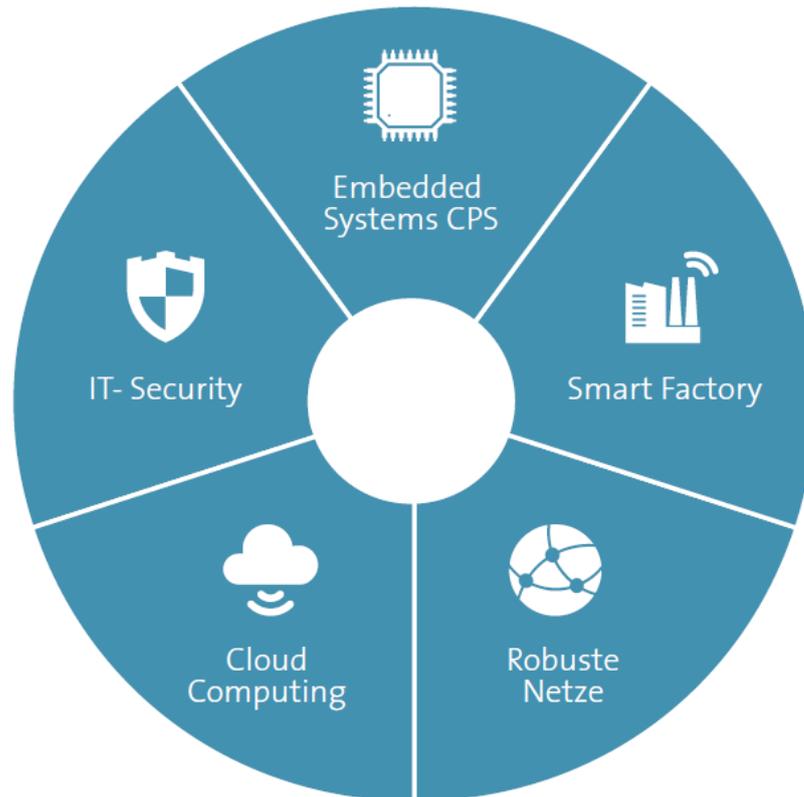


Figure 65: Technology Fields Considered in the Study (source: (Bauer et al., 2014))

Collectively these are seen as the cornerstones of future production and success.

Why the concept is relevant: I4.0 is seen as industrial digitalisation, the end-to-end digital integration within a Smart Factory that focuses on real-time, intelligent, horizontal and vertical networking of people, machines, objects and ICT systems for the dynamic management of complex systems (Federal Ministry for Economic Affairs and Energy, 2020), that are geared towards increasingly individual customer requirements, (Gilchrist, 2016; pp 195). It is an enabler toward the capable and upgradeable requirements identified for Tempest.

6.8.5.2 FESTO Model

A slightly different view of Industry 4.0 by FESTO, see Figure 50, pp 140. It has similar technological fields at its core, and is a simple guide for some of the most used terms associated with automation and I4.0, some of which are described in the context of an aerospace factory of the future.

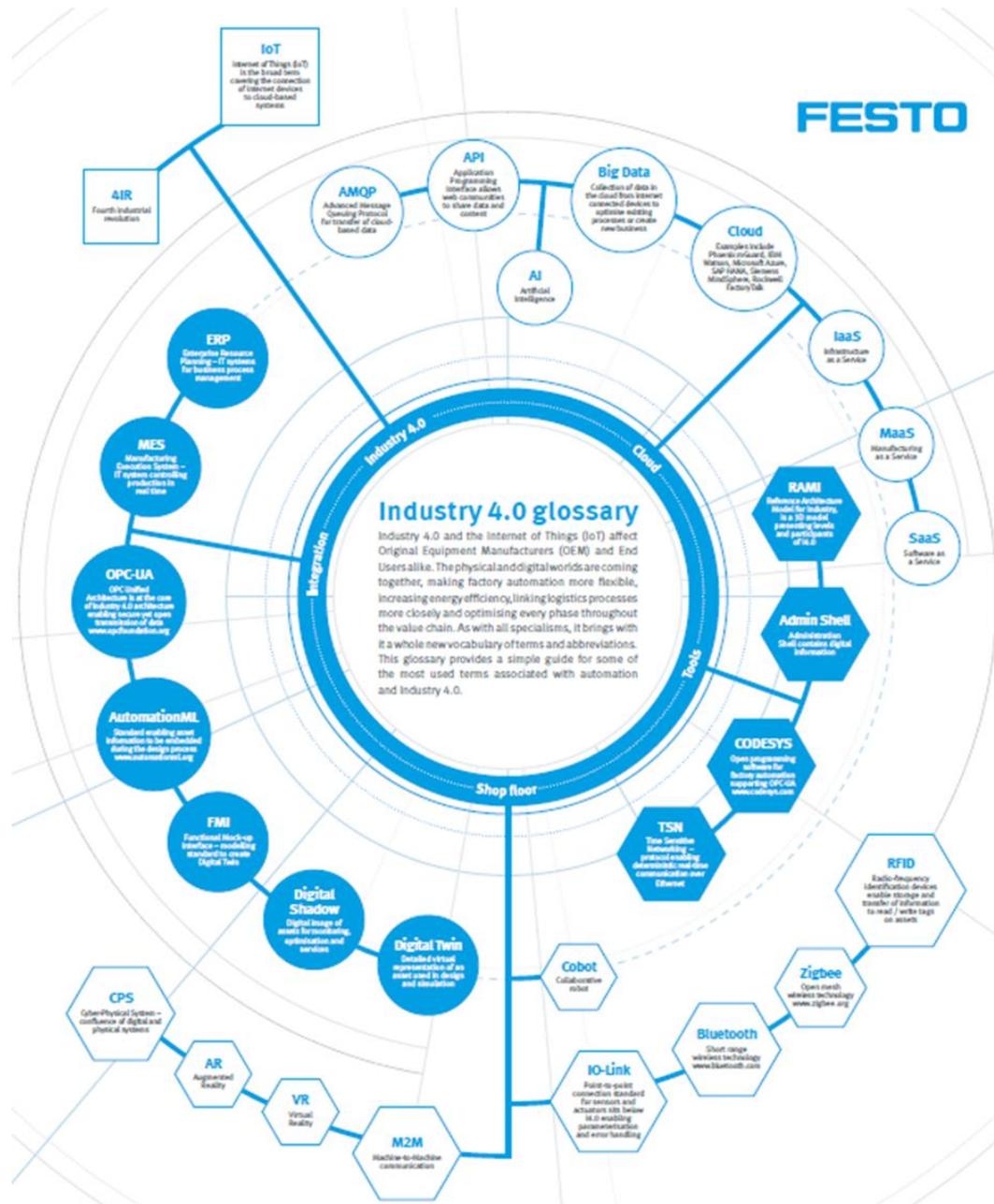


Figure 66: FESTO Industry 4.0 Glossary (source: FESTO)

6.8.5.3 Industrial Internet of Things

What is the concept: Industry has had sensors and collected data from them to control operations for decades, similarly it has had machine-to-machine communications and collaborations for a decade hence core technologies for Industrial Internet of Things (IIoT) are not new. The difference is the scale of operations. Vast amounts of data, sometimes termed Big Data, can now be generated, collected, stored and then analysed using advanced analytics hosted in the cloud.

Why the concept is relevant: IIoT is an enabler, it will allow factories to be termed “smart” and connected. Delivery of instructions to operators and smart-tools, along with real-time visualisation will allow self-awareness, self-prediction and self-comparison.

6.8.5.4 Cyber-Physical Systems

What is the concept: Cyber-Physical Systems (CPS) are an integration of physical assets and computational capabilities (Baheti and Gill, 2011), and with the ever growing use of sensors and networked machines, they now have the ability to continuously generate high volumes of data, termed Big Data. With the aid of IIoT, an architecture proposed in Figure 67, pp 141, (Lee et al., 2015), enables a CPS to be constructed from the initial data acquisition to the analytics and value creation.

Why the concept is relevant: The integration of new technologies such as IIoT and CPS into industrial processes will enable entirely new opportunities such as new business models and work organisations, (Bartodziej, 2017); and it is part of the route to intelligent, resilient and self-adapting assembly systems.

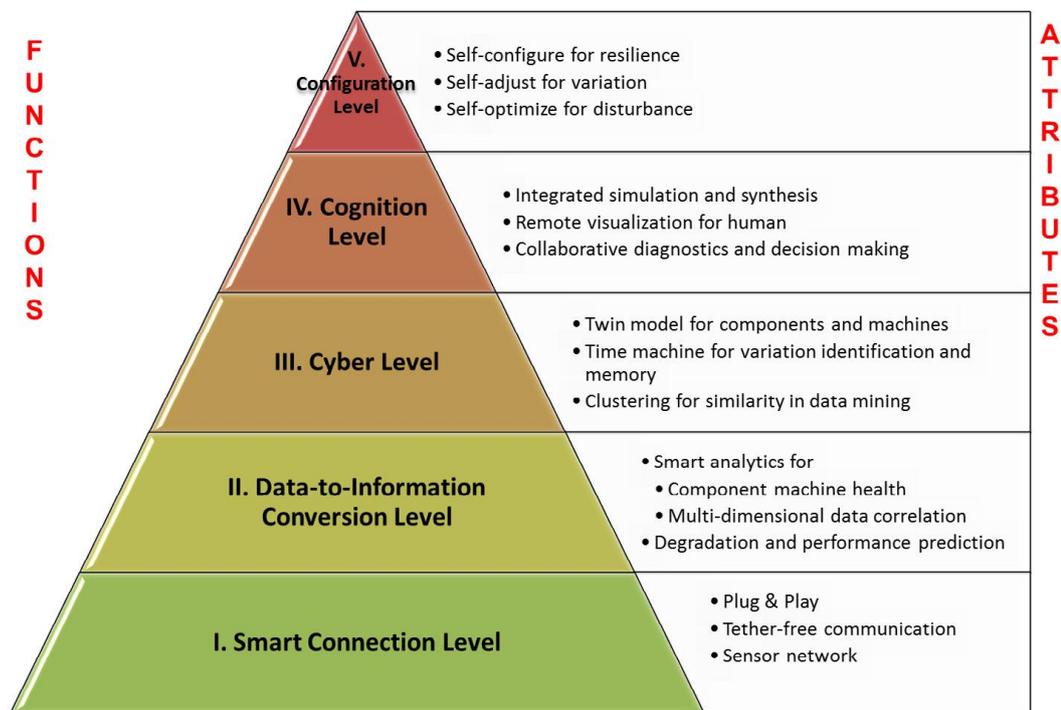


Figure 67: 5C architecture for implementation of Cyber-Physical System

6.8.5.5 Big Data

What is the concept: The term Big Data probably only came into widespread use in the last decade, around 2011, and the hype around it can be attributed to IBM and similar technology companies who had invested in the then niche analytics market, (Gandomi and Haider, 2015). IBM described Big Data in four dimensions, volume, velocity, variety and veracity, and pointed out it is not about the data but the value that can be extracted from it, or deriving value (meaning) from it in a whole new way.

About the same time, NASA and the US Air Force published papers on the Digital Twin concept, (Tuegel et al., 2011), and paradigm, (Glaessgen and Stargel, 2012). The concept, hypothetical, was delivery of a new air vehicle in 2025 (coincidentally the same timeframe that Boeing will delivery initial operational capability on the TX programme, and they have unveiled a DT as part of their MBE Diamond – see Figure 64, pp 137). At the same time, hypothetically, an As-built digital model with an estimated 1000 billion degrees-of-freedom is supplied. It is ultra-realistic in geometric detail, including manufacturing anomalies. This data is then used to virtually fly the aircraft, outputting structural performance and damage data.

Why the concept is relevant: Data can be collected to be analysed to improve the process, record what has been made, and create opportunities for new business models, particularly in testing and in-service support.

6.8.5.6 Reference Architectures

What is the concept: The traditional reference architecture for automation has been ANSI/ISA 95. It was created to develop an interface between the enterprise and control systems; it does however have limitations when it is considered in the context of I4.0, different industries from process to factory automation have different standards, technologies, associations and standardisation organisations.

Reference Architecture Model Industrie 4.0 (RAMI4.0) was developed by experts in the area of I4.0 and cyber-physical systems; it includes the Life Cycle & Value Stream of systems and products involved in industrial production processes (IEC 62890), the Hierarchy Levels of batch control (IEC 62264 and IEC 61512), and six architectural interoperability layers covering aspects related to business, functions,

information, and communication, as well as physical assets and their integration, (Frysak et al., 2018), see Figure 68, pp 143.

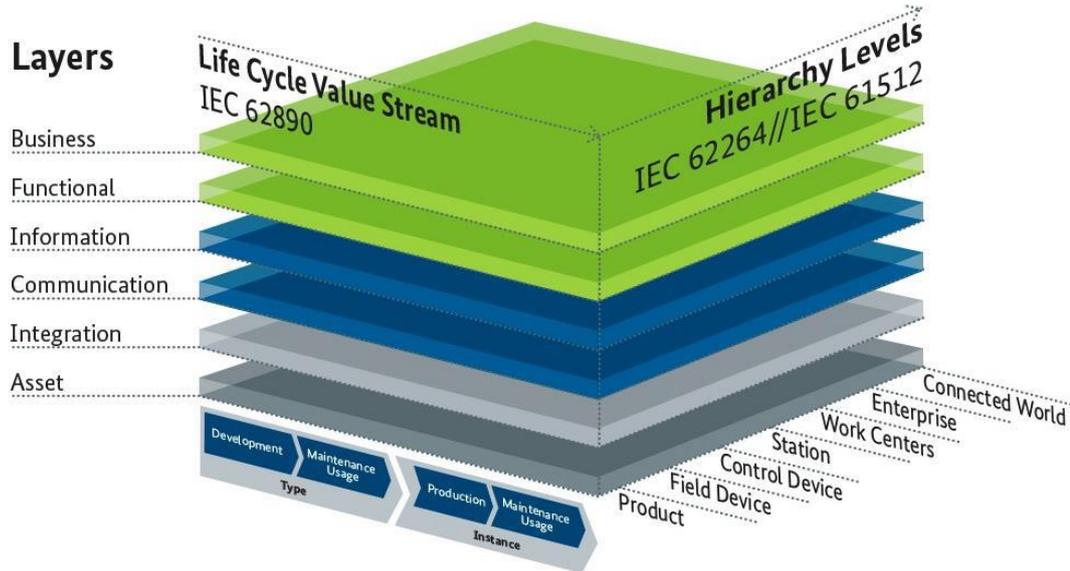


Figure 68: RAMI4.0 Model (source: Platform Industrie 4.0 and ZVEI)

6.8.5.7 Reconfigurable Assembly Systems

Reconfigurable Manufacturing Systems (RMS) were proposed as a solution to the uncertainty manufacturing companies faced in the 21st century, (Koren et al., 1999), by being very responsive to market changes. This responsiveness was achieved with reconfigurable machines and reconfigurable controllers, as well as methodologies for their design and rapid ramp-up.

RMS is a very broad concept, and one key element is Reconfigurable Assembly Systems (RAS), the design of which is based upon well-defined system requirements matched to uncertainties and changes, so that the right mechanism can be selected to meet them, (Bi et al., 2007).

The assembly cells of the future in aerospace will need to reconfigure during the assembly of a product because the volumes will be low and equipment will be repurposed. RMS/RAS are designed from the outset for rapid change, hence the methodologies for design and change need to be explored and employed, otherwise if change takes too long or is too complex then the benefit of having automation will be lost.

6.9 Conclusions and Recommendations

6.9.1 Engineering Objectives

Two engineering objectives were identified at the start of this research. By using metrology to guide standard industrial robots it was demonstrated that the traditional assembly fixture could be replaced by a flexible, reconfigurable, and reusable alternative, which would have significant benefits for the non-recurring costs on a project.

Replacing the very accurate but expensive machine tools requires a number of innovations. It was shown that part-data collected during their manufacture could be converted into a model which subsequently could be printed using an Additive Manufacturing process, to create a shim to fill a gap; a process known as Predictive Shimming. Part-to-part drilling during detail manufacture allowed both one-way assembly and ICY assembly to be demonstrated; with the later significantly reducing the drilling time by 20:1, and both negated the multiple installation and removal of a part, shortening and simplifying the assembly of the structure.

Alternative methods of undertaking the drilling currently performed on the machine tools was not demonstrated, but options were investigated. Those available included the use of accurate robot technology, Metrology Assisted Robot Automation (MARA), and a version of Measurement Assisted Determinate Assembly (MADA). These robots are all portable so allowing them to be taken to the assembly as opposed to the current method which involves taking the assembly to the machine tool. They will significantly reduce the non-recurring costs, and enable a more reconfigurable factory of the future.

6.9.2 Business Need

Affordability was identified as the business need, both individually and collectively the innovations described in this report can create a more affordable airframe for Tempest. It was shown that through the use of automation both the non-recurring and recurring costs can be reduced. There is also the opportunity to create new business models, particularly for ownership of the assets and in-service support.

This research led to the creation of four patents. The business benefits to these are two-fold. Initially, they protect the investment in the research and demonstrate to others our interest in airframe assembly, supporting the business metrics of the

company. Secondly, if it can be shown the patents are used in the manufacture of airframes in the future, then there is a financial benefit through a process known as the Patent Box.

6.9.3 Recommendations

The recommendations from this project are:

Overall: The concept of the model-based enterprise should be invested in/considered, and on the Tempest project the partnership with Saab explored, to build up knowledge and understanding for 2 to 3 years hence when greater clarity of the project will be publically known. Discuss the creation of digital twins for manufacturing and assembly processes, as well as of the products, with a view to building a new business model for the latter as part of the in-service support, and predictive modelling of the life of the airframe.

Design: Introduce model-based definition with process and manufacturing information, and follow an iterative process of examining joints to design for particular manufacturing processes and assembly methods. Design the gaps in the joints based upon manufacturing process capability available both in-house and sub-con, explore the gap/no-gap option, and consider the inclusion of sensors embedded or printed onto shims.

Manufacture: Explore new or alternative NC programming systems and include finite element analysis to minimise distortion of parts during manufacture. Add the use of metrology into Design/Manufacture cycle discussed above, and create measurement plans for data to build the digital twins and support the predictive processes. Introduce rules with respect to the use and order/direction the holes are drilled on machine tools. Investigate new paint processes that provide better control of thickness, and include it as an off-set, in both manufacture and assembly. Plan for drilling painted part both to nominal and determinate off-sets. Further explore the additive manufacture of shims, the materials and the processes, with the options of make versus buy, applying at detail manufacture or on assembly, and if direct-write is a viable option.

Assembly: Demonstrate other products such as front fuselages and wings/fins can be assembled using the automation developed. Develop the use of simulation, for tolerance analysis and virtual assembly, as well as for assembly planning including

the reconfiguration of the assembly system. Determine the safety road-map to create the original vision of automation and human operating in an open environment, applying “guarding” as needed. Explore the use of collaborative robots, either supporting the operator to undertake a task, or undertaking the task on its own. Create the end-to-end digital integration needed to build the Smart Factory of the Future, including the use of the cloud with the appropriate level of IT security.

6.9.4 Final Thoughts

In the context of digitalisation and the smart factory, this research contribution has primarily been directed at the physical, with an element of virtual assembly as part of the digital twin and the virtual world. A minimum viable physical system configuration has been demonstrated upon which further systems can be added to achieve the concept of a smart factory.

Additional systems that could be added include, but are not limited to; logistics systems using RFID tags for tracking and recording with mobile autonomous robots (MAR) to deliver parts then utilising end-of-arm tooling and robots at point of use, planning their routes using SLAM techniques. Internally-owned G5 networks that allow device-to-device communication, and the use of wearable devices to assist operators. Collaborative and cooperative robots, that work with an operator or in unison respectively. Smart tools and sensors that work together with operators, and record progress to confirm build quality in real-time.

The data collected about the product can be used to support the customers and well as improve future designs, while the data on the process can be analysed to provide new insight. Of significant importance will be the safety systems. New methods need to be adopted to ensure there is a balance between the various states, or phases, of an assembly system such as when it is reconfigured, being re-used, or re-purposed on another product. Ideally safety procedures could be implicit in the underlying digital system. Digitalisation also offers the potential opportunity for the technical documentation to be automatically generated through the enactment of the engineering processes. The processes will need certification in a digital manner to operate efficiently.

Many of the stakeholders, both internal and external, will require educating in the new approach that digitalisation offers through integration and connectivity using

suitable open standards. It will mean changes to existing business models, which potentially will disrupt current relationships, and trust will need to be developed in many areas, which could include the ways in which IP is held, controlled, and shared.

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Appendix A: FCAS and Tempest

A1.1: FCAS

Future Combat Air System (FCAS), started life as the Future Offensive Air System (FOAS), which itself was preceded by a number of minor studies on generic future combat aircraft dating back to the late 1980's.

It is described as a System of Systems (SoS), which can be best defined as:

(SoS) connects the seemingly different parts with the whole to solve large-scale problems. (Purdue University, 2019)

The example used by Purdue University's College of Engineering to distinguish between a complex system and a system of systems is air travel. An aircraft is a complex system, many systems must work together otherwise the aircraft won't fly. An airport is another complex system, but it involves aircraft, support trucks, baggage-handling equipment, and many other systems. In an airport the systems can and do operate independently of each other, but for it to function there needs to be the correct mix of these systems, and they need to cooperate with each other; this makes an airport is a system of systems.

Therefore FCAS is not just an aircraft.

A feasibility study on Future Offensive Air System (FOAS) was launched in October 1997, then following the 1998 Strategic Defence Review (SDR) (Pike, 1999), a number of concept options were explored by the MoD to replace the capabilities provided by the Tornado GR4. The targeted in-service date was 2018, when the Tornados reached the end of their operational life.



Figure 69: FOAS Manned Option (source: BAE Systems)

FOAS options which included manned aircraft, Figure 69, pp 159, looked at variants of developed aircraft such as Eurofighter and F-35, rather than a new build, as well as unmanned air vehicles (UAV), Figure 70, pp 160, Conventional Air-Launched Cruise Missiles (CALCM), and C4ISTAR⁹.



Figure 70: FOAS Unmanned Option (source: BAE Systems)

FOAS was run in parallel with two other defence initiatives, the new future aircraft carrier (CVF) and the Future Joint Combat Aircraft (FJCA), which was previously called Future Carrier Borne Aircraft (FCBA) and had been launched in 1996 to meet Staff Target 6464. In September 2002, the STVOL variant of F-35 (F-35B) was selected as FJCA.

The same defence review reported on a study that had looked at replacing the *Invincible* class of aircraft carrier. In January 1999 companies were invited to tender for the assessment phase; then in November two consortia were briefed to produce up to six designs, capable of carrying between thirty & forty FJCA. The contract was in two-phases, the first phase formed part of the aircraft selection, while the second reduced the risk on the preferred design option. The final submissions were made in November 2002, just after F-35B had been selected as the FJCA, and the down-select was made in January 2003. It was over five-years before the contract for CVF was signed and it became known as the Queen Elizabeth-class. The expectation was they would enter front line service in 2018.

⁹ C4ISTAR is Command, Control, Communications, Computers, Information/Intelligence, Surveillance, Targeting Acquisition and Reconnaissance

FOAS was one of the pilot Integrated Project Teams (IPTs), part of the new Smart Procurement Initiative (SPI), but was closed down in June 2005

The FOAS was replaced by Deep and Persistent Offensive Capability (DPOC), which itself was canned in the 2010 SDSR. Two programmes that were part of DPOC, were Future Combat Air Capability Programme and Strategic Unmanned Aerial Vehicle Experiment (SUAVE). While FCAC looked at the force mix of air and missiles already being procured, SUAVE investigated UAV technologies.

One of the projects under SUAVE was Taranis, which started in 2006, and was shown to the public in July 2010 at BAE's Warton site, in Lancashire. Costing £143m, it was an industrial collaboration that took 3.5 years & over one million man-hours to produce. First flight planned for 2011 was initially delayed until 2012, then delayed further to August 2013. In 2014, the experience gained from Taranis was combined with the French UAV called NEURON, to become FCAS.

For clarity, the above information is mapped as far as the 2015 SDSR in Figure 71, pp 162.

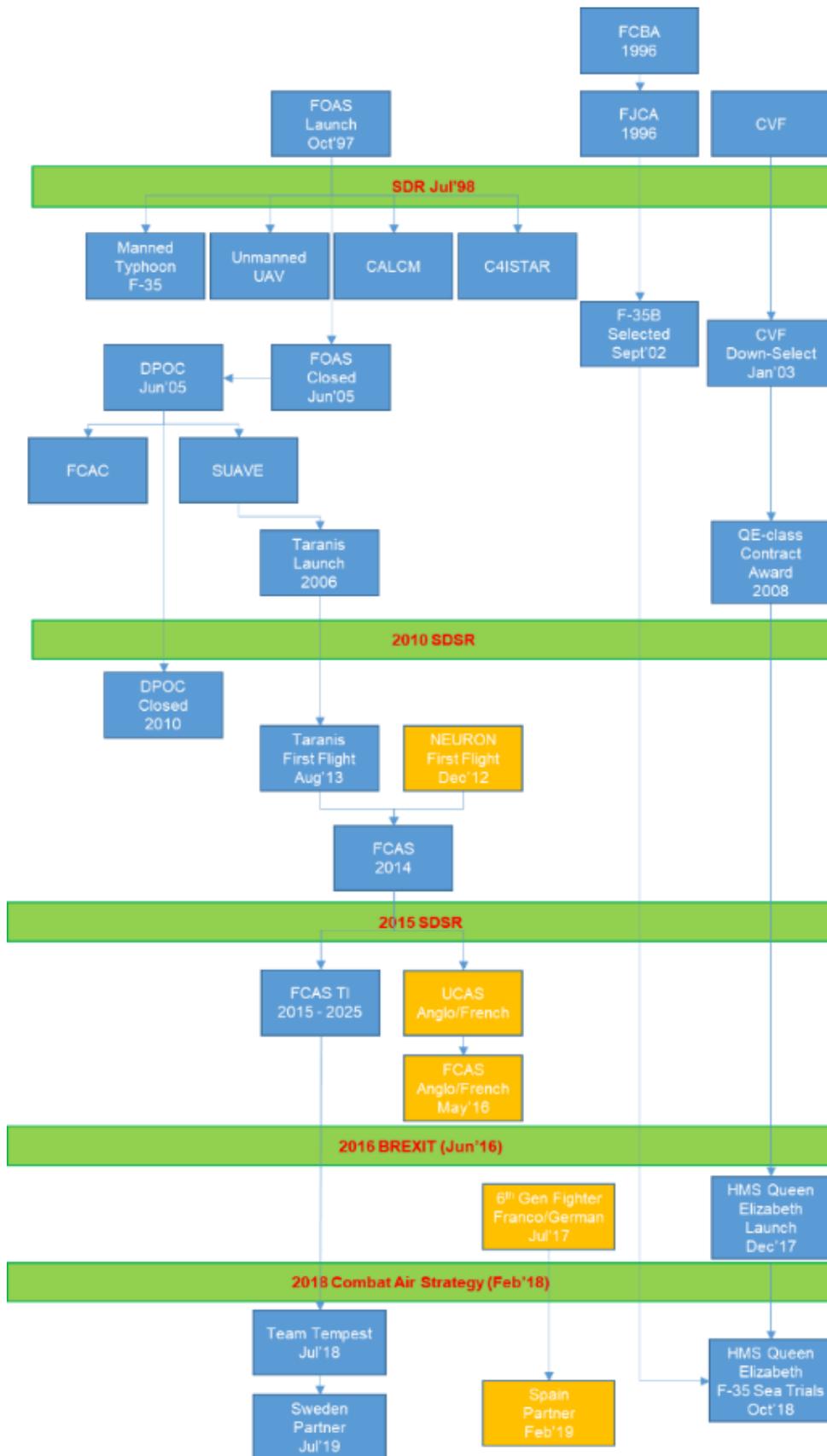


Figure 71: Route from FOAS to Tempest

A1.2: Team Tempest

When this research started in late 2014 the considered opinion was the next generation air vehicle would be an Unmanned Air Vehicle (UAV). This was based on the fact that the UK & French governments had signed an agreement earlier that year to undertake a £120m joint feasibility study (Ministry of Defence UK, 2014). The study used the experience gained by BAE Systems' on TARANIS and Dassault Aviation on NEURON. The contract was part of Future Combat Air System (FCAS), and the result of the Lancaster House treaties on defence and security cooperation signed in 2010 between the two nations. It had a notional in-service date sometime in the 2030s.

The 2015 SDSR allocated £2bn budget over the next 10-years to the Future Combat Air System Technology Initiative (FCAS TI) and stated the UK would invest in the next generation of combat aircraft technology, in partnership with the UK defence industry and its closest allies, (H M Government, 2015: para 4.50). It also reaffirmed the UK would work with France to develop an Unmanned Combat Air System (UCAS).



Figure 72: UCAS Model (source: BAE Systems)

This was further reinforced in 2016 when the governments jointly announced a £1.54bn project to build a prototype of the Future Combat Air System (FCAS), (Airforce Technology, 2016). The plan was to transition to the next phase during 2017, and prepare for the full-scale development of UCAS operational demonstrators by 2025, Figure 72, pp 163. The MoD had “pencilled-in” a technical review for 2020, possibly aligned to the 2020 SDSR, with the platform serving as a basis for future operational capability beyond 2030.

The 2015 SDSR did not mention a Combat Air Strategy; that was announced three-years later in February 2018, (Ministry of Defence UK, 2018a) and confirmed in March the same year when the National Security Capability Review stated:

... the intent to create a Combat Air Strategy was announced in 2018. (Cabinet Office, 2018)

Between these two events, while presenting Dassault's 2017 financial results their chief executive, (Thisdell, 2018) said FCAS was now just "marking time", and he was "disappointed" by the stalling of it; Why did he make this comment?

In July 2017, France and German had agreed to jointly build a 6th generation fighter jet to replace their Rafale and Typhoon fighter jets by 2040, (Tran, 2017). While casting doubt on the Anglo French project, it politically signified a strong European defence and greater unity following the vote by the UK to leave the EU 12-months earlier; referred to as Brexit. It also united two rivals in aerospace that have historically been in competition. The announcement also said that in the future the project would be opened up to other European states.

The following year at the ILA Berlin Air Show in April a 10-page *common requirements document* was signed, and Airbus (jointly owned by Germany, France and Spain) announced it would partner Dassault.

The agreement was confirmed in June when it was announced France would take the lead, and by November it was said work would start in 2019, with more specific details being given at the Paris Air Show in June 2019. A two-year Joint Concept Study (JCS) was then announced as starting in February 2019, (Allison, 2019).

At the 2019 Paris Air Show in June, a mock-up of FCAS/SCAF (Système de Combat Aérien Future) 6th generation stealth fighter, called Next Generation Fighter (NGF) was unveiled and the Spanish Defence Minister signed an agreement for Spain to join the program as a partner nation. Further details of the composition of the FCAS/SCAF SoS were given too, besides NGF there will be Remote Carriers (RC) and an Air Combat Cloud (ACC), the prototypes of which will flying by 2026.

However it wasn't just the French who were proposing an alternative air vehicle. At the Farnborough International Air Show in July 2018, Team Tempest was unveiled, (Hoyle, 2018).¹⁰

Team Tempest comprised of BAE (UK), Leonardo (Italian), MBDA (UK-French), Rolls-Royce (UK) and the RAF's Rapid Capability Office.

Tempest too is described as a 6th generation fighter jet, which is manned and optionally unmanned. The vision or concept, Figure 73, pp 165, includes technologies such as a virtual cockpit, and in the context of this research, is an affordable vehicle which is up-gradable, manufactured with advanced digital and process tools, and "Designed for Growth".



Figure 73: Team Tempest Future Combat Air System Concept (source: BAE Systems)

Also announced at Farnborough was the Combat Air Strategy. It reiterated the joint investment of over £2bn by Government and industry to sustain and enhance key skills and capabilities. This includes starting the critical next phase of the National Programme, providing investment in key UK design engineering skills. While

¹⁰ [Team Tempest 2018](#)

currently excluded from the Franco German project, Tempest too is not against forming partnerships with other nations.

Currently, FCAS TI is expected to demonstrate between 50 – 60 technologies, and will be followed by a more production-focused initiative.

While Italy, (Kington, 2019), has suggested it might join the project at RIAT 2019 Sweden, (Hoyle, 2019), did join, but Saab, manufacturer of the Gripen will not join the Team Tempest industry grouping, rather they will work in cooperation, “to scope out joint development and acquisition programmes for both nations”, Andrew says, (Hoyle, 2019).

Appendix B: Design Rules for Technical Standards

Manual

The following are a set of “rules” or guidance based upon findings from this research which need adding to an Automated Assembly section in the Technical Standards Manual.

- The design should consider modules that can be customised to create bespoke sub-assemblies, and assemblies.
- A common spacing of frames would enable a common working-zone for both operator and robot, and tailor the need of the metrology.
- The common method(s) of locating the part on the end-effector, such as zero-point clamping.
- The design should consider frames with pockets as the parts with the variation, and will contain the majority of the angle-head drilling.
- Dreamer and angle-head overall length relative to the size of the pocket.
- The pockets need to be a minimum size to accept the zero-point clamping unit.
- The size of the gap between the parts should be based on machining and treatments (painting, coating) capability.
- The lap-joint should be used where practical, with the datum face of a shear-web or floor as an interface.
- Where practical build vertically to minimise the effect of gravity, and minimise free hanging structure.
- Embed in the design process an assessment of the design against the various part-to-part assembly methods; ICY/DA, MADA and one-way.
- After ICY/DA, MADA and one-assembly drilling methods have been considered some form of tooling will be necessary.
- Alignment of the part CoS and the assembly methodology, particularly if Determinate Assembly is used.
- Drill hole patterns, top-to-bottom, inboard-to-outboard, and forward-to-aft.
- If possible mirroring the design either side of Y0, the airframe centreline, to enable sharing of end-effectors.
- Assume an additively manufactured shim as opposed to as liquid shim.

- Create a nominal shim in CAD to enable tolerance analysis software to be used.

Appendix C: Patent Abstracts

XA5296 – ABSTRACT TITLE:

A METHOD AND APPARATUS FOR PRODUCING COMPONENT PARTS OF AIRCRAFT AIRFRAMES

- (57) A method of producing a component part 202, 204 (e.g. frame 202, shear web 204, see figure 2) of an aircraft airframe 200 comprising providing a first digital model of the component part, producing an initial physical part using the model, measuring a surface of the initial physical part, creating a second digital model (of the initial physical part) using the surface measurements, digitally assembling the second digital with a further digital model (of a further component part of the aircraft frame), specifying fastener hole(s) 606 through the assembled digital models, each fastener hole comprising aligned first and second portions passing through the second and further digital models respectively, drilling fastener hole(s) in the initial physical part using the second digital model with respective first portions of the fastener hole(s) specified therein, thereby producing the component part of an aircraft airframe.

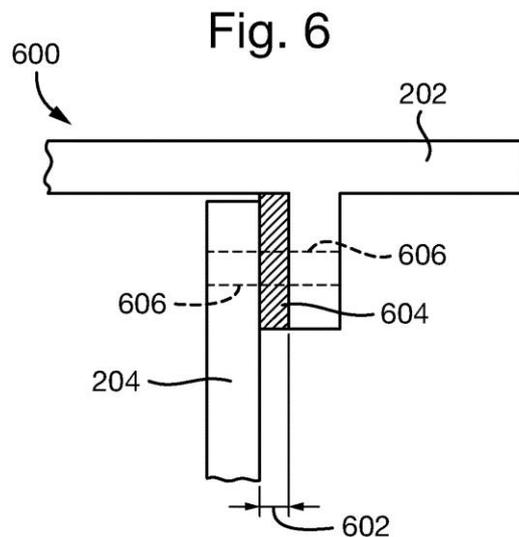


Figure 74: Fig.6 Application GB 2576410 A

XA5297 ABSTRACT TITLE

A METHOD AND APPARATUS FOR PRODUCING AT LEAST PART OF AN AIRCRAFT AIRFRAME

- (57) A method comprising providing a plurality of component parts 202, 204 of an aircraft airframe 200, measuring a surface of each component part, creating a digital model of each component part therefrom, digitally assembling together the digital models to produce a digital model 600 of at least part of the aircraft airframe, using the digital model to create a digital model of a shim 604, the digital model of the shim 604 filling a gap between at least two digital models of component parts in the digital model of at least part of the aircraft airframe, producing a physical shim using the shim digital model, attaching the physical shim to a component part, measuring a component part surface with the shim attached, creating a new digital model of the component part with the shim attached using surface measurements of that component part with the shim attached.

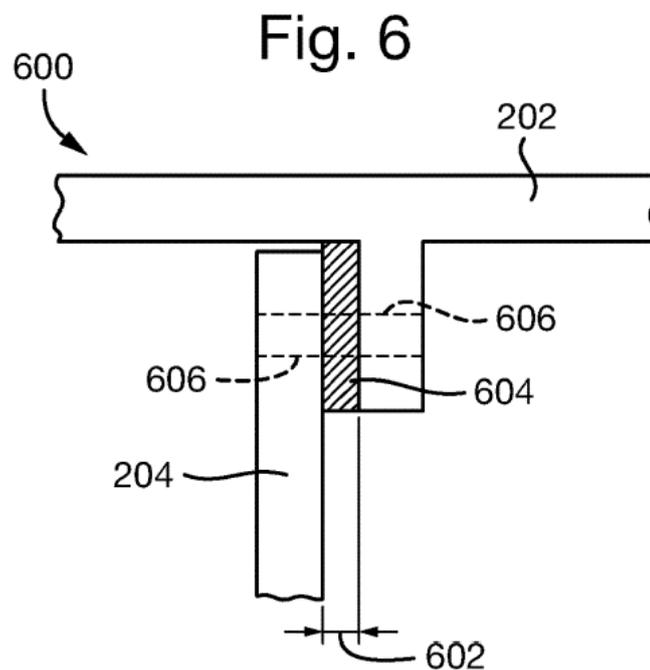


Figure 75: Fig.6 Application GB 2576412 A

XA5317 ABSTRACT TITLE

A METHOD AND APPARATUS FOR ASSEMBLING AIRCRAFT AIRFRAMES

(57) A method and an apparatus for assembling aircraft airframes are provided. The assembly method comprises providing a digital model of at least part of an aircraft airframe, the digital model comprising digital models of each of a plurality of component parts of the a airframe, providing the component parts, each comprising one or more predrilled fastener holes, fixing a first component part 202a to a support structure 1102, fixing a second component part 204a to an end effector 1112 of a robot arm 1110, using the airframe digital model controlling the robot arm to move the second component part relative to the first component as specified in the airframe digital model, causing predrilled hole(s) in the second component part to align with predrilled hole(s) in the first component part, attaching the second component part to the first component part using fasteners through the aligned predrilled holes.

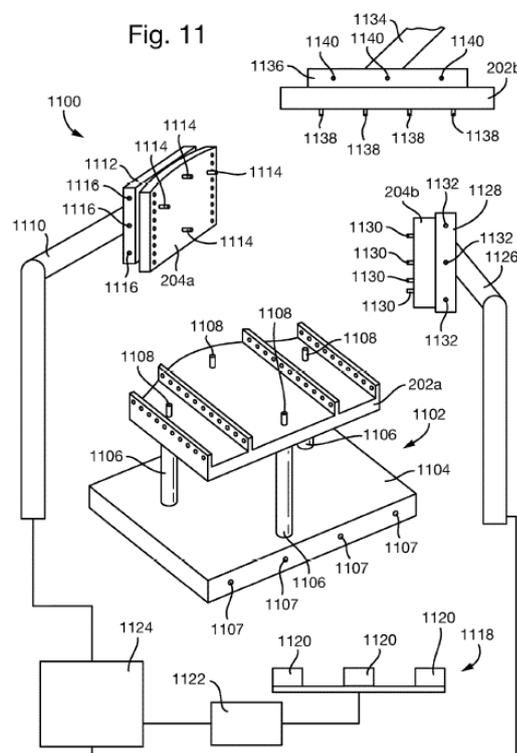


Figure 76: Fig.11 Application GB 2576411 A

XA5318 ABSTRACT TITLE**A METHOD OF APPLYING A SHIM TO AN AIRCRAFT AIRFRAME**

(57) A method for applying a shim 1500 to an aircraft airframe 200, comprising providing an aircraft airframe 200, measuring a surface of the airframe, creating a digital model of the airframe using those measurements, providing an aircraft skin 1506, measuring a surface of the aircraft skin, creating a digital model of the aircraft skin using those measurements, digitally assembling the airframe and aircraft skin digital models, using the digitally assembled models to create a digital model of a shim 1500, the digital model of the shim substantially filling a gap between the digitally assembled airframe and skin digital models, performing an additive manufacturing process to form shim directly onto the surface of the aircraft frame using the digital model of the shim. The method may include printing the shims onto the surface, producing highly accurate, precise shims on the aircraft airframe, facilitating proper attachment of the aircraft skin without adhesive usage.

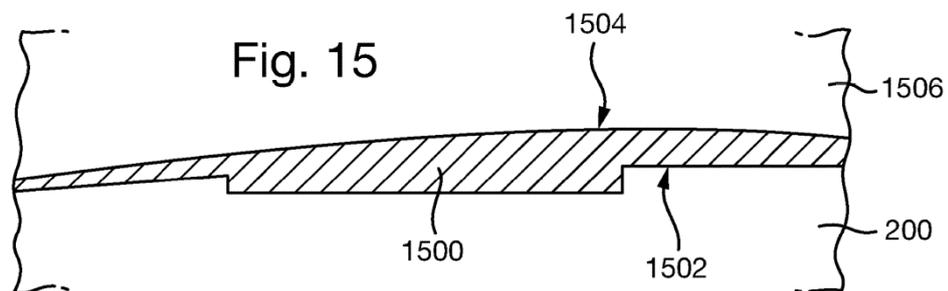


Figure 77: Fig.15 Application GB 2576413 A

Appendix D: TX Programme Chronology

An example of a fast-jet that has challenged perceptions of affordability is the USAF's new T-X fast-jet trainer. The competition for the contract and three of the seven entrants are described in the next few sub-sections, then how this might have been achieved is discussed.

D1.1: T-X Fast-Jet Trainer Programme

The USAF started developing the requirements to replace the Northrop T-38 Talon, their fast-jet trainer that entered service 50-years ago, in 2003 with entry to service in 2020 to meet the expected requirement from F-35 as it entered service.

A fatigue failure and loss of an aircraft in 2008, advanced the in-service date to 2017, but budget constraints forced the USAF to make choices, and the requirements were not released until March 2015. In December 2016 the formal request for proposal (RFP) was released, with initial operational capability (IOC) in 2024. Down select was made 27th September 2018.

The original DoD budget was \$16.3billion for 350 aircraft and an associated “live, virtual and constructive” ground-based training enterprise.

Initial seven partnerships and individual aerospace companies expressed an interest, offering a mix of existing and new designs. Only four submitted bids, three dropped out and two of those were Textron AirLand, and the partnership of Northrop Grumman and BAE Systems. The next two sub sections will look at these two, identifying why they dropped out.

D1.1.1: Textron AirLand - Scorpion

Textron AirLand, a joint venture between Textron and AirLand Enterprises, had proposed its Scorpion light attack jet, with its design based upon a market survey rather than the traditional requirements specification. Designed to sell for under \$20million each, and cost between \$2,000 and \$3,000 per hour to fly, the estimated market for the trainer was over 2000 units world-wide.



Figure 78: Textron AirLand Scorpion (source: Textron Airland)

Scorpion went from a “blank-sheet of paper” to first flight in less than 2-years, by using COTS equipment and performing wind-tunnel tests after the actual wings had been manufactured; this shortened traditional development timescales. With everyone on the project was housed in one building decisions could be made in hours rather than days; another way of shortening the timescales.

The Scorpion was a twinjet, so would require some modification to meet the RFP, which sought a single engine solution. Swapping the two engines for a single engine would require changes to the wing too, Figure 78, pp 174.

While initially expressing an interest and confirming the necessary modifications would be made, in Sept’ 15 the offer was withdrawn, citing the USAF requirements change from a low-cost advanced jet trainer to a high-performance fly-by-wire trainer with top tier handling qualities.

This highlights two interesting points, not every air force wants a twin-engine jet, and once a fast-jet is designed improving its performance significantly may not be practical. Two points worth noting given Tempest current twin-engine configuration.

[D1.1.2: NGC/BAE – Scaled Composites Model 400 Swift](#)

Initially the partnership of NGC & BAE had proposed an updated version of the Hawk T2/128, believing this to be a low-risk, low-cost strategy. Then in early 2015

it was withdrawn due to shortcomings in the airframe performance against the evolving requirements and its affordability.

Meanwhile NGC used the advance design and prototyping techniques available at its subsidiary Scaled Composites to manufacture a purpose-built aircraft for the competition, Figure 79, pp 175.



Figure 79: Scaled Composites One-piece, Three-spar, Composite Wing (source: Scaled Composites)

Codenamed Model 400, Figure 80, pp 175, the plan was to officially unveil it in early 2017, but that never happened, because in February, NGC and BAE jointly announced they would not submit a proposal, which they judged “would not be in the best interests of the companies and their shareholders.”



Figure 80: Northrop Grumman and Scaled Composites Model 400 (source: Scaled Composites)

This proposal highlighted again the difficulty up-rating the performance of an airframe once it has been designed, and how the customer's requirements evolve in the early part of the program.

D1.1.3: Boeing and Saab – T-X & Black Diamond

The winner of the T-X competition was the Boeing and Saab partnership, and their clean-sheet design, which came in more than \$10billion less than the USAF / DoD original budget estimate. The “indefinite-delivery/indefinite-quantity contract” will allow the USAF to buy up to 475 advanced jet trainers and 120 simulators for no more than \$9.2billion, but the current plan is to purchase 351 T-X trainers and 46 simulators, with an initial order for 5 jets and 7 simulators at \$813million; Have Boeing and Saab created a *disruptive affordability template* for new product development?

If not, did they buy into the program by submitting a money-losing price to secure the contract, with the aim of recouping any losses over the long-term with revenue from sustainment, modernization and derivatives.

Both companies, quite rightly, have been very cautious about revealing how they have achieved this, but it goes back to July 2015 when Boeing revealed the presence of a project, that had been on-going since 2012, called Black Diamond. It is a combination of advanced technologies and processes developed and evolved over years.

Very little is known about the project partly because it is based in the Phantom Works, where many of the products and technologies being developed are classified. The purpose of the Phantom Works is to take new technologies developed by Boeing Research and Technology (TRL 1 – 3), and grow them into prototypes (TRL 4 – 6) which the businesses then turning them into products (TRL 7 – 9).

Black Diamond is company funded, so free from government security regulations. The cited goal beginning to advance the state of the art in two disciplines, namely, engineering that is based on detailed computer models that include physical properties, and use of robotic to fabricate and assemble airframes. There are reports of a demonstrator, the purpose of which was to “infuse” more automated assembly into complex aircraft structures, but no images are available; Boeing currently use robotics to fabricate and assemble simpler shapes and structures, such as circular

sections of fuselage and wing skins onto spars and ribs. Black Diamond's aim is to take this to the next level, on complex, compound-curved shapes and internal structures, while achieving high precision. All characteristics of stealth. To aid this Boeing are looking to have parts pre-drilled by suppliers, so that final assembly is a fit and fasten process; implying no further drilling, necessitating strip and deburr.

One of the possibly projects that has come out of Black Diamond was Fuselage Assembly Upright Build (FAUB), an automated drilling and riveting systems that is on wheels or AVGs, making it flexible, Figure 81, pp 177.



Figure 81: Fuselage Assembly Upright Build (FAUB) (source: Boeing)

Pairs of robots, probably using Kuka cooperating robot technology, work inside and outside the fuselage, drilling and installing rivets in an all-aluminium stack. The external robot carries a multi-functional end-effector (ex. Alema Automation, Fr.) while the internal robot supports the structure and bucks or set the rivet.

Saab, who too have made no comment, have been praised by the Phantom Works as having an engineering culture whose paperless model-based systems engineering approach is the same as Black Diamond's. An aim for both companies is to use MBE to steepen the learning curve, with the objective of achieving today's cost levels by the 10th unit rather than the 100th. One industry standard is to achieve standard time at the 180th aircraft, Saab seeks to achieve it by the 30th on JAS 39E, halving the hours taken on the first 100 aircraft.

Maintenance of T-X has been simplified, the high set wing allows stand-up access to doors and inspection points, while drop-down panels on the lower fuselage provide quick access to systems. Interchangeable left and right rudders, stabilators, and actuators simplifies the supply chain.



Figure 82: Boeing Saab T-X Prototype (source: Boeing)

Boeing adopted what has been described as an “extreme approach” to model-based engineering (MBE), and while not new or unique to Boeing, they have taken it further than others. Critically, they have been able to take the process through to production, giving them an opportunity to prove it out and decide if it does save time and money.

Another factor was the use of an agile approach to software development; in place to the traditional large blocks of code written over many months. The functions were broken down into smaller chunks, which were integrated at a systems level every 8 weeks. This reduced the number of lines of source code (SLOC) by 50%, (Ferguson, 2018). If, as estimated on F-35 the Avionics and Mission Systems accounts for 40% of the cost, reducing the number of SLOC by 50% will impact the price.

The key point however is Boeing do not consider the two aircraft that they have built to be prototypes, Figure 66, pp 178, instead they refer to them as engineering and

manufacturing development (EMD) ready. Their argument being, while they did not have the final specification when the aircraft were designed, but they got very close, some things do need modifying, which is the delta for the EMD aircraft; critically the mould-line does not need changing, hence EMD-ready.

This goes slightly against convention. It has been common practise to re-design a fast-jet at the start of the development phase; Boeing appear to be implying this is not necessary, and are attributing it to their use of MBE.

The first two aircraft were assembled without shims on minimal tooling, with a re-work rate of only 0.3 per cent, and the overall assembly process taking 80 per cent fewer hours than it was estimated a traditional build would take. Two examples are quoted, attaching the canopy transparencies to the cockpit frames and splicing the fuselage section together. Using a sealant technology the gluing of the transparency to the frame in place of traditional drill and fasten was reduced from six-weeks to eight-days; while the splicing the sections together, which normally would take 24-hours, took 30-minutes.

There are a number of points about this bid of note, and impact this research.

Firstly, Boeing and Saab may have created a disruptive affordability template, which coming in at under 50% of the budget, questions the ability of the DoD and MoD to estimate the cost of future programs. It should be noted too that this is a single-engine, all metal aircraft, which is simpler in comparison to a 5th generation combat aircraft.

While the TRLs at the various stages of development is standard model world-wide. Black Diamond is associated with what is known as “the valley of death”, TRL 4 – 6, and it is in-house, not a catapult centre. It is an overarching drive (or strategy) to use more Model-Based Engineering (MBE) and robotics, T-X is just a product of it. Focusing on complex, compound curved shapes and high precision implies stealth is an objective too.

Getting the suppliers to pre-drill holes (un-specified) and having minimal shim will enable one-way assembly, and contributes in some-part to needing 80% less assembly hours. If less hour correlates to fewer operations, so less for the operator to learn, then achieving a steeper learning curve and getting to standard hours

significantly earlier, will be significant saving as the program ramps-up. Two other point are the links to the suppliers, and how MBE has supported this.

Finally, the concept of agile software development and the need for fewer lines of code, while aimed at the Avionics and Mission Systems, may have a place in an evolving, reconfigurable assembly system. The concept of agile development in a manufacturing environment needs exploring.