COMPRESSED DESIGN AND VALIDATION

Culture & Digital Tools

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

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ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions and recommendations of the project.

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come.

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Lead author

Neil Hunter
Technologist – Verification and Validation

Co-author

Will Markiewicz

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EXECUTIVE SUMMARY

Aircraft development can commonly take six to eight years from a formal programme launch to entry into service. Development timescales could be even longer with the introduction of the revolutionary technologies necessary to achieve a zero-carbon emission aircraft.

Delays in bringing such an aircraft to market carries cost: a cost for maintaining a cross-functional development team on the project for longer than planned; a cost for having to carry the project commercial burden longer before recouping it through delivery; a cost from loss of market share as competitors catch-up or overtake; and above all, a cost to the environment for every flight that is not taken on a zero-carbon emission aircraft. To maximise the reduction of carbon emissions from aviation, we should seek to accelerate entry into service as much as possible.

The challenges and complexities of incorporating such revolutionary technology into a commercial aircraft design must not be underestimated. Entirely new liquid hydrogen fuel technology and associated systems are necessary which have not previously been used in commercial aerospace and carry a high degree of uncertainty.

This paper focusses on how **culture** and **technology and tools** can reduce the time to market for hydrogen powered aircraft and their components.

The scale and speed of investment into hydrogen aerospace technology bricks will also have a major impact on the time it takes to bring a hydrogen powered aircraft to market and is addressed in the FlyZero report 'The Case for the UK to Accelerate Zero-Carbon Emission Air Travel' **[1]**.

The recommendations for action on culture and technology and tools that the UK aerospace community can take to accelerate technology development are:

- Promote adoption of a more agile culture in the aerospace sector.
- Enable access to digitalisation resource and new tools within the UK supply chain.
- Coordinate modelling frameworks across industry to streamline collaborative working between teams and organisations and enable greater tool diversity.
- Champion the democratisation of data to support early model and tool validation.
- Progress critical liquid hydrogen test infrastructure at a national scale to support necessary technology characterisation and systems integration testing.
- Encourage progressive cooperation with regulatory authorities on the path to certification for hydrogen-fuelled aircraft.

In addition, the paper highlights the following considerations for individual companies working to compress the timeline for design and validation. These need to be championed at an executive management level and backed up with multi-year investment in training, tools and infrastructure.

- Embed efficient design and validation good practices.
- Shift the organisation to a more agile culture.
- Formulate a digitalisation strategy to enable collaboration in a digital twin / digital thread engineering environment.
- Adopt an end-to-end model centric (MBSE, MBE), data-driven approach to optimise design and validation activities.
- Embrace early testing and simulation to manage uncertainty and data gaps.
- Progress critical test infrastructure for liquid hydrogen systems.
- Prepare early groundwork for certification, especially around the certification challenge topics: liquid hydrogen fuel system, crashworthiness, hydrogen explosion prevention and environmental protection.

01. INTRODUCTION

Aircraft development times can commonly take six to eight years from a formal programme launch to entry into service (EIS), i.e., technology readiness level (TRL) 6 to TRL 8 [2], with TRL 6 representing the point that the technology is considered validated for design into a production project. Development timescales could be even longer with the introduction of the revolutionary technologies necessary to achieve a zero-carbon emission aircraft. FlyZero has identified liquid hydrogen as the zero-carbon emission fuel with the greatest potential to scale to large commercial aircraft [3]. Realising these radical new aircraft will require major technical challenges to be overcome.

Cumulative carbon dioxide emission reductions are strongly affected by how quickly large (narrowbody and midsize) commercial hydrogen-powered aircraft can be brought to market in volume. Figure 1 shows the carbon dioxide abatement for two of the market scenarios modelled by FlyZero [4] [5]. The disruptive scenario accelerates R&D development to ensure that large aircraft are entering into service in the mid-2030s, in time to meet the most likely fleet replacement windows. In the current trend scenario, this opportunity is missed and larger aircraft do not start to enter service until the mid-2040s.

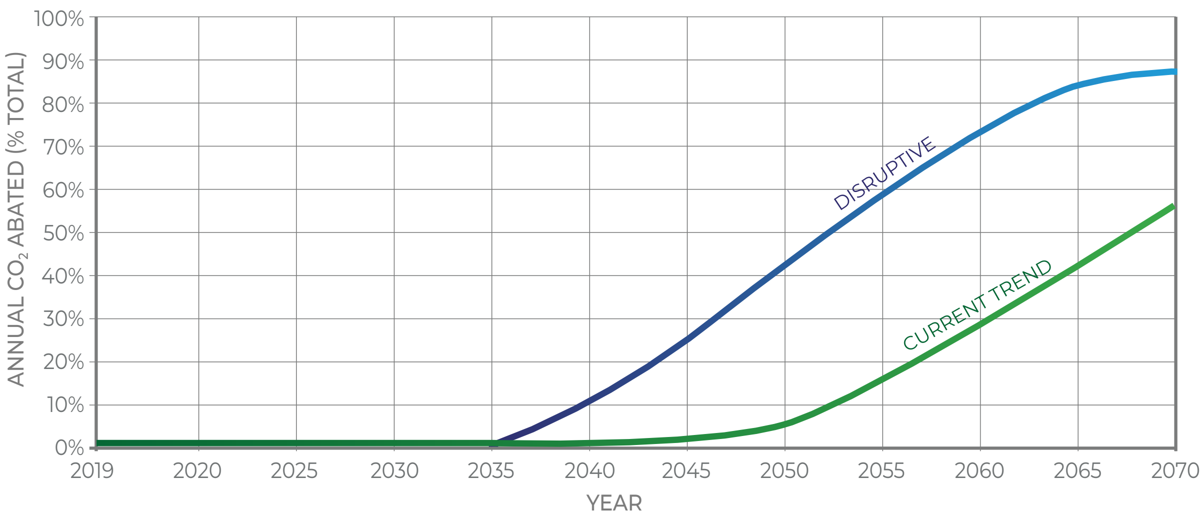


Figure 1 – Cumulative abated carbon emissions for two FlyZero scenarios – 'disruptive' and 'current trend'. Adapted from the FlyZero Market Forecasts and Strategy Report [4]

Companies first to the new hydrogen aircraft market will have a competitive commercial advantage, increasing the opportunity to win customers and deliver a longer, smoother production run.

The aerospace industry is traditionally conservative, with a necessary focus on design safety, performance, and reliability. Whether by plan or circumstance, these priorities result in long design and validation timescales, driven also by design complexity. Design complexity results in an increasing likelihood of unpredicted interactions occurring at every level, hindering project progress **[6]**. Despite the addition of computational tools such as computer aided design or finite element models over the past 30 years, FlyZero has found that development timescales have been trending up over that same period.

The scale and speed of investment is expected to have a major impact on the time it takes to bring a hydrogen powered aircraft to market and is the subject of the FlyZero report 'The Case for the UK to Accelerate Zero-Carbon Emission Air Travel' **[1]**.

This paper focusses instead on how **culture** and **technology and tools** can reduce the time to market for hydrogen-powered aircraft and their components.

The paper will discuss individual opportunities to compress design and validation cycles and any barriers specific to those opportunities in **Sections 2** and **3**. Examples of how the different cultural and technology elements link together are included in **Section 4**.

The opportunities captured here are the conclusions from a series of studies conducted by FlyZero with support from CFMS. These studies include reviews of academic literature and industry publications and interviews with representatives from several leading UK aerospace companies, academia, consultancies and professional organisations.

The findings are taken from research in the aerospace, defence, automotive and energy sectors. They are intended to be abstract and generalised enough that they can be potentially used in whole or part for different system levels and technologies, across both major original equipment manufacturers (OEMs) and suppliers.

This paper is not a good practice manual for systems engineering or product design, it only discusses opportunities that directly benefit compressed design and validation. Most if not all of these may have additional benefits too, such as reduced cost, improved stakeholder satisfaction or better design optimisation.

02. CULTURE AND MANAGEMENT

This section covers the theme of organisational culture and managing project teams within that organisation. Figure 2 below shows a summary of the section on culture and management opportunities.

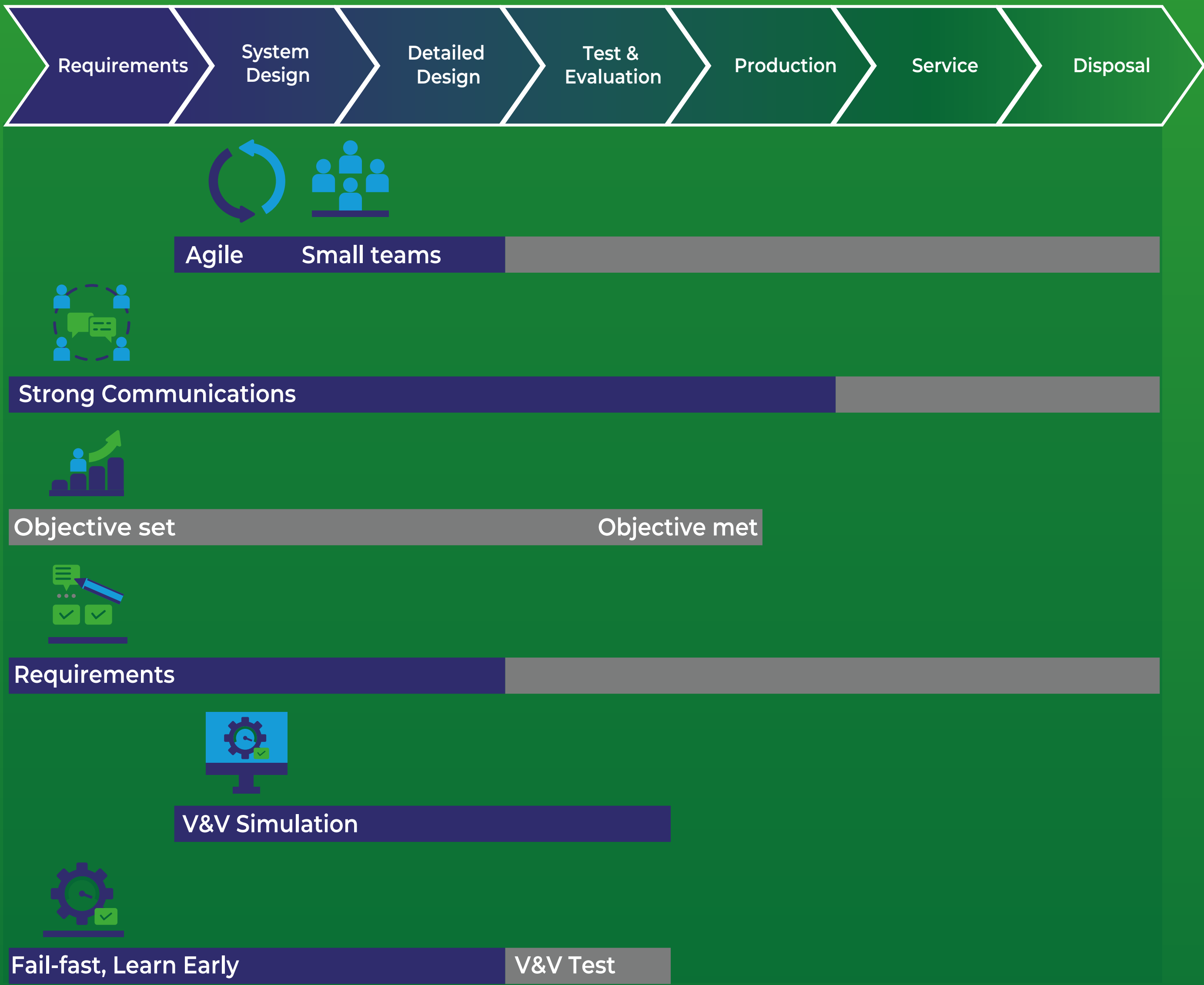


Figure 2 – Typical application of culture and management opportunities within the product lifecycle

This section will look at opportunities grouped as follows:

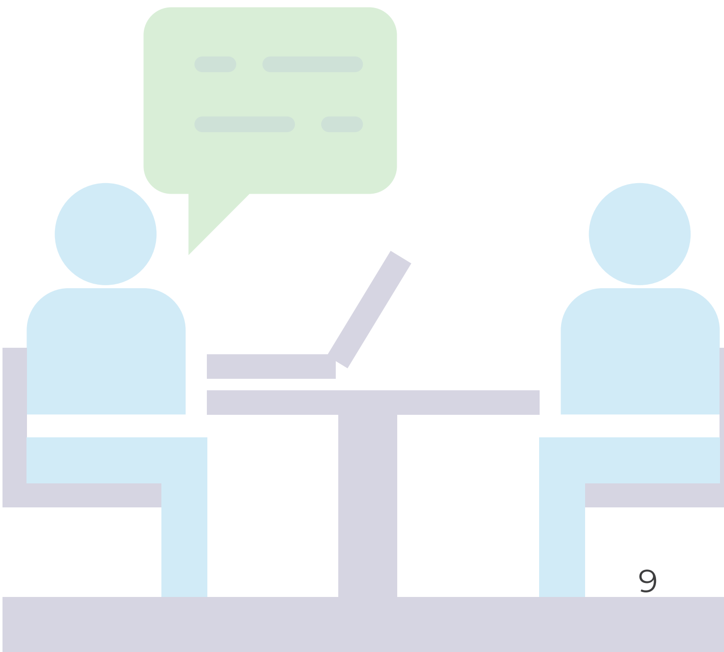
02.1 INDUSTRY FEEDBACK

During FlyZero, interviews were held with industrial organisations on the topic of management and culture. The interviews revealed broad, though not universal, consensus on the enablers to compressed design and validation, which included:

- Rapid decision making and streamlining the drawing release process as much as appropriate without compromising safety, including better supplier delegation.
- Avoidance of changes in scope, requirements, interfaces and assumptions.
- Faster and more rapid testing, with a “fail-fast, learn-early” culture.
- Improved communication and information flow, coupled with a culture of continuous progress in all areas.

The opportunity and scale to which the companies interviewed are currently able to apply these enablers varied by organisation and product complexity. There is emerging use of agile methods, but wider adoption is partly hampered by rigid company structures, slow changes in mindset away from conventional waterfall approaches and disenchantment having met significant challenges when applying agile, which was originally used for software development, to a hardware-centric development programme. Perhaps above all, leadership was cited as being critical to driving the above best practices.

Details of how the FlyZero project itself was managed are found in the FlyZero ‘Innovation and Project Management’ paper **[7]**.



02.2 LEADERSHIP AND ORGANISATION

The primary opportunities for compressed design and validation within leadership and organisation for an aerospace organisation delivering a zero-carbon emissions aircraft are:

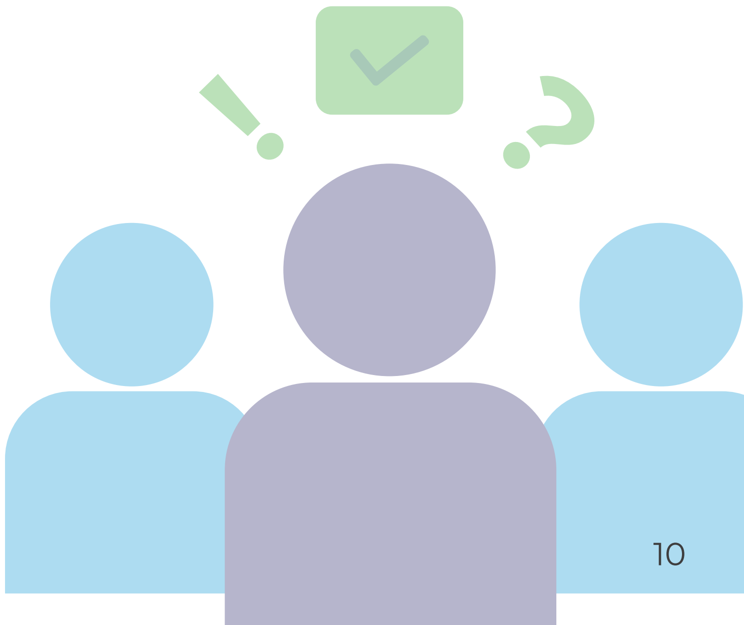
- **Leadership** – empower delegation; marginal gains; single vision
- **Teams** – small, focussed teams; flat hierarchy
- **Communication** – be specific, concise, and directed
- **Agile development** – requirements focus; rigour; continuous improvement

Leadership

The project lead must have practically complete control of the project, with authority to make quick decisions regarding technical, financial, or operational matters. They should be supported by a small but strong and capable leadership team. Problem resolution should be conducted at the lowest practical level, with competent persons empowered to make delegated decisions thus removing bottlenecks and reducing delays.

Senior leadership must set clear expectations of vision, pace of work, behaviour and how challenges can be managed quickly and effectively. Organisational and cultural changes need to be championed by senior leadership from board-level down and necessitate a multi-year investment in communication, training and continuous improvement [8] [9].

All levels of the organisation need to seek out and apply the concept of marginal gains in everything they do, the cumulative result of which can be significant in a competitive market landscape.



Case Study 1 – Skunk Works

The Skunk Works at Lockheed Martin has been an early pioneer of many of the leadership and organisational enablers discussed in this paper, including “Kelly’s 14 Rules” [9] [10]. Adopting this culture has given Skunk Works a long-held reputation for being able to deliver complex and revolutionary aircraft programmes in impressive timescales that continues to this day. Such successes include developing the A-12 Mach 3+ aircraft (SR-71 predecessor) from concept to first flight in less than four years, achieving first flight of the “Have Blue” stealth technology demonstrator in 18 months, and delivering the first production F-117 stealth fighter four years after project launch [9].

Communication

Timely communication is fundamental to the efficient and progressive work of a team and should be specific, concise and directed. Infrequent or inconsistent communication leads to lack of common understanding and a reduction of trust. Conversely, excess communications are inefficient and can lead to information overload. Interactions between individuals are at the heart of any team and fostering good interpersonal skills will facilitate smoother collaboration and information sharing between individuals, by recognising that everyone brings unique perspectives, experience and understanding to the team [6].

Project Teams

Integrated project teams should be kept as small as practically possible in a flat, organic structure. Smaller teams enable easier coordination, reduced demands on communication, and can be more easily ‘ring-fenced’ to focus on critical tasks. Teams should be multi-functional, incorporating both technical domains (e.g., design, manufacturing, service) and non-technical domains (e.g., financial, commercial), and consist of individuals who can provide sufficient breadth and depth across all disciplines [9].

Appropriate incentive structures based on project goals rather than siloed successes are essential to promote collaboration and compromise to maximise efficiency. Every person needs to move in the same direction and be personally motivated by the goal of achieving zero-carbon emission flight as soon as possible.

02.3 AGILE DEVELOPMENT PRACTICES

Just as there is value in the ability of a system to adapt and respond to changing conditions, there is also value in a development approach that adapts to change and uncertainty in cost, stakeholder needs and technological limits – especially in a project introducing revolutionary new technology to aerospace [11].

Agile practices, first developed for software development, were created to encompass this flexibility. There are several agile practices (e.g. scrum, scaled agile framework, etc.), but all embed flexibility to changes in requirements, development iterations (often referred to as sprints) and small cross-functional teams. The effective application of an agile approach can significantly accelerate project pace (see **Case Study 2** below).

The top-level system configuration needs to be sufficiently matured before flow-down of requirements to lower levels. This prevents lower-level designs being sub-optimised or subject to later rework if top-level requirements change (see **Figure 3**).

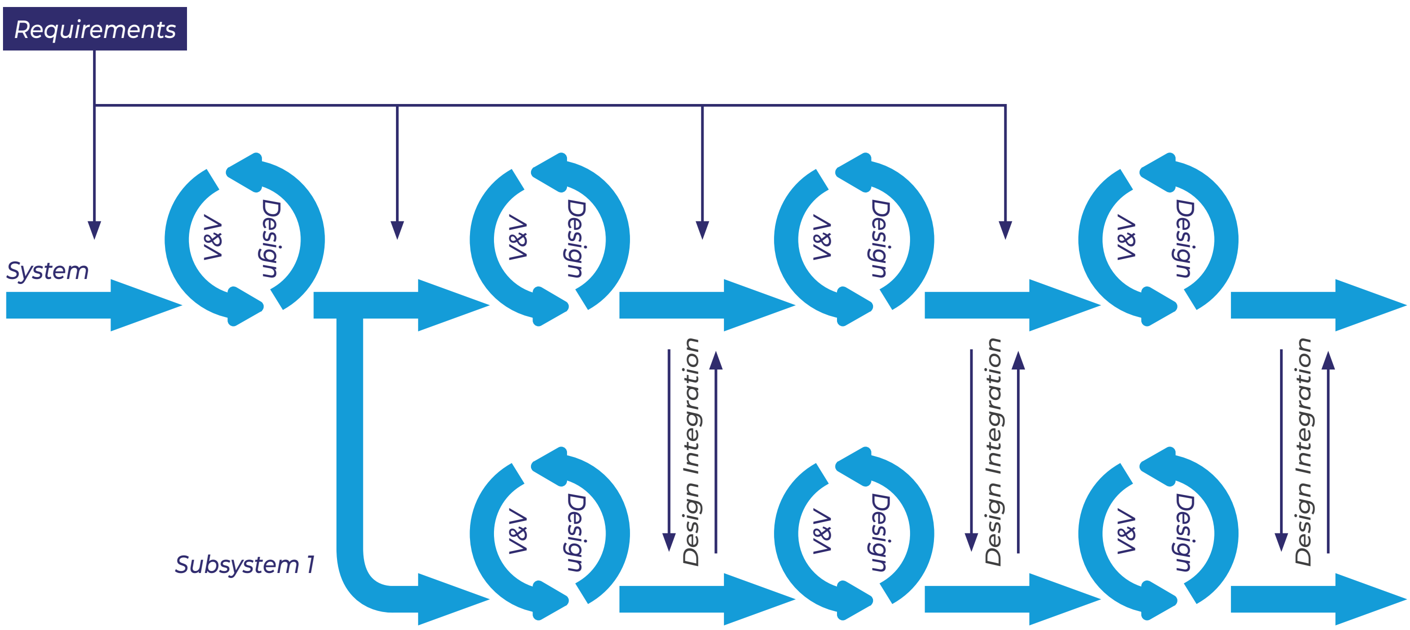


Figure 3 – Agile workflow through sprint loops for a system and subsystem. The system level architecture needs to be sufficiently mature before flowing down to subsystem levels

Optimal Trajectory

To optimise a project within the time domain, there are potential advantages to mapping design progress as a series of visualised key parameters based on stakeholder features (the "Why"), technical behaviour (the "What") and physical architecture (the "How").

An agile approach then enables regular and validated feedback of progress along a trajectory in the presence of uncertainty, which can be more precisely and quantitatively controlled (see **Figure 4**) **[11]**.

Project elements of the system progress in unison, while still providing the necessary design freedom to engineering teams.

Iterations may also be grouped to aid synchronising development across complex systems. For example, to develop the Gripen E fighter, SAAB used 'development steps' to align major functional releases, divided into three-month increments and three-week sprints **[12]**.

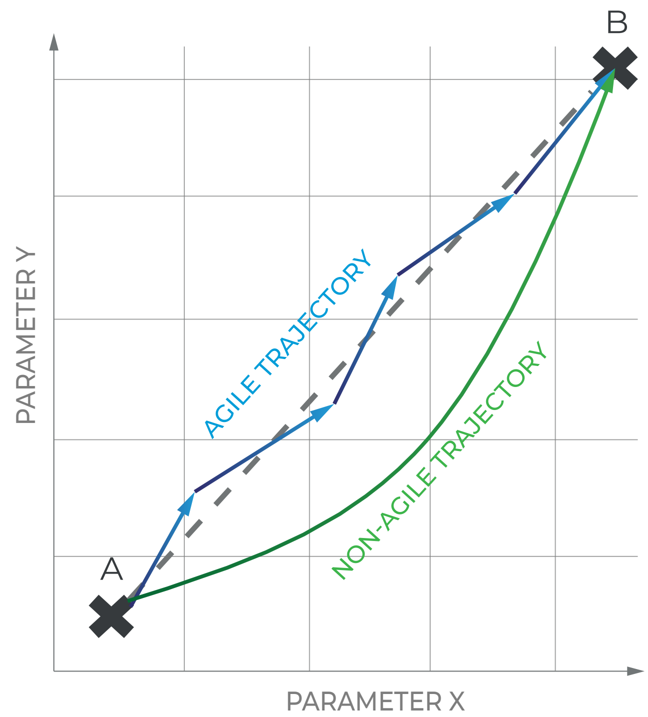


Figure 4 - Optimising project progress using agile increments

Case Study 2 – FlyZero Midsize Aircraft Concept Iteration Sprint

FlyZero applied a ring-fenced multidisciplinary sprint team to optimise the concept fuel burn and range. This involved design changes across system interfaces to aircraft architecture, fuel tank, engine by-pass ratio and payload-range assumptions.

A legacy approach would likely have taken up to **three months** due to several formal communication loops to understand system performance and design across interfaces and to amend documented requirements or assumptions for successive iterations.

Using an agile, model-centric approach, the team had the visibility across functional and physical interfaces. They could directly see the impact of changes in real time, enabling rapid iteration to the optimal design point in **one week**, while simultaneously communicating that to other teams via the model.

Parallel Design Philosophies

A cross-functional structure performs significantly better on radical innovation projects, whereas a more traditional functional structure performs better on incremental design projects [13].

A zero-carbon emission aircraft will include a mixture of new, revolutionary technology as well as iterative, evolutionary technology derived from legacy commercial aircraft designs. Different practices or design philosophies could be used in parallel (see Figure 5).

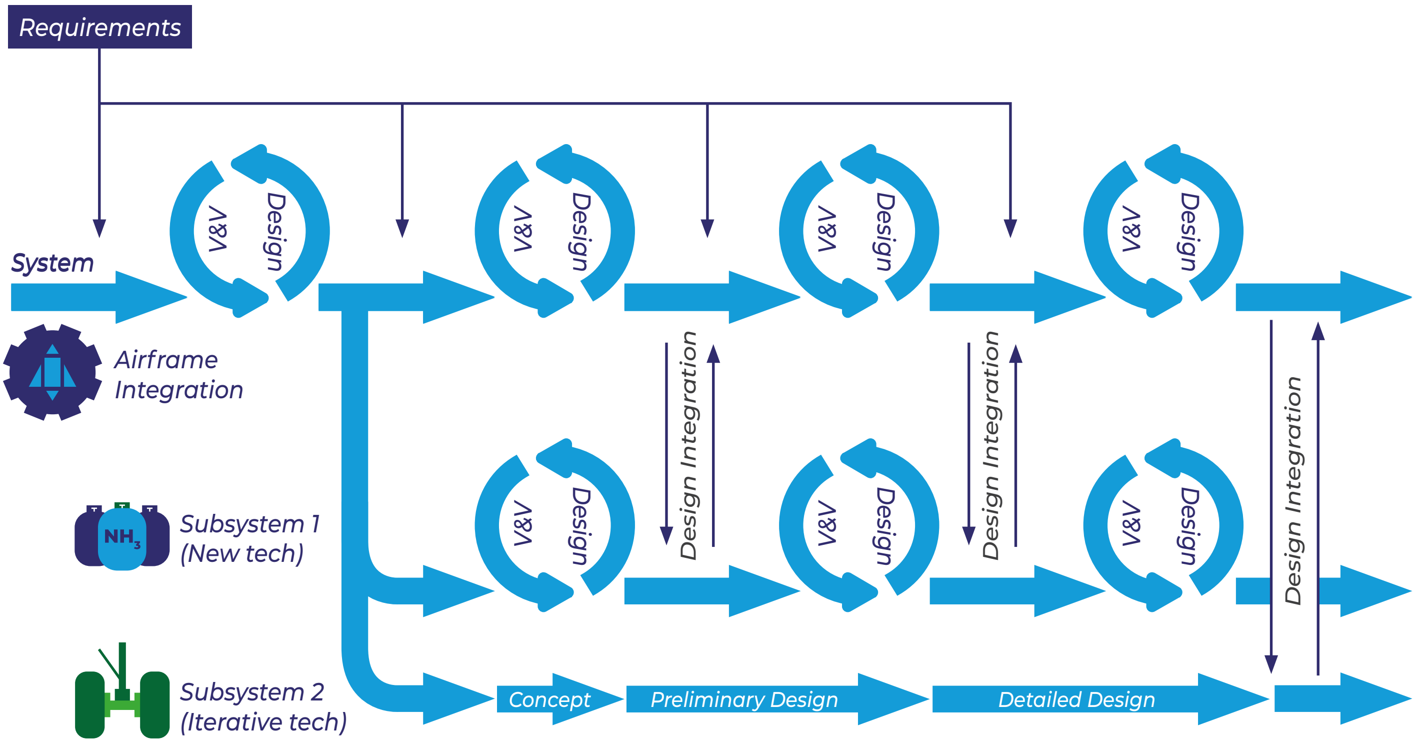


Figure 5 – Applying agile and waterfall in parallel for new and iterative technology respectively

Some scalable approaches, such as the scalable agile framework (SAFe) are flexible in how they dictate agile to lower levels, accommodating both agile and non-agile development methods of subsystem and components [14]. These characteristics would make them suitable for such projects that bring together a mixture of revolutionary and evolutionary technologies. The consideration and adoption of all other cultural and technology enablers would remain the same for both approaches.

Case Study 3 – Volvo Cars

Volvo, with 40,000 employees producing 700,000 cars a year, was able to transform into an agile organisation across its entire product line in two and a half years. Using SAFe, Volvo improved speed to market and responsiveness to emerging technologies while also improving product quality. With the chief technology officer as lead champion, the transformation was implemented through a Program Increment Planning approach with common cadence to manage the many cross-dependencies across the organisation, spending 150,000 manhours on workforce training and training 2,000 leaders in the mechanics and the behavioural changes for SAFe [15].

02.4 REQUIREMENTS, VERIFICATION AND VALIDATION

Opportunities relating to requirements, verification and validation not only accelerate those activities, but they also compress design. Specific opportunities include:

- **Managing uncertainty** – balanced approach; progressive decision making.
- **Requirements validation** – manage volatility; keep concise; capture assumptions.
- **Verification** – increased simulation; early fail-fast testing; integrated test infrastructure.
- **Certification** – strong evidentiary trail; regulator collaboration.

Managing uncertainty

The introduction of radically new zero-emission technologies to an aircraft will inevitably come with uncertainty and risk, in the performance of the technology itself and in the integration of that technology. This may result in a drive to eliminate uncertainty, however doing this too early can limit the opportunity for innovation and for optimisation (and so avoidance of downstream rework). Instead, a balance is needed to consciously determine an acceptable degree of uncertainty to carry forward.

The Design Council's double-diamond concept is a useful way to approach uncertainty by encouraging iterative divergent and convergent thinking at different stages in the development cycle [16]. This aligns with an agile approach and can be applied at any system level.

The pace of decision making in the presence of uncertainty should consider not only the cost of risks but also the cost of delay. A progressive decision-making approach breaks down larger decisions into smaller ones that carry less individual risk. If a smaller individual decision turns out to be wrong, progress can be quickly backtracked and recovered [17].

Requirements Validation

While uncertainty around solutions is manageable and, to a degree, desirable, a stable top-level objective is essential to ensure the project teams work efficiently towards a common goal.

Volatility of requirements has historically been a major contributor to poor project delivery [18]. This is especially the case in technology development where the market for the first product may be unknown or changing. The consequent uncertainty in requirements must be managed:

- Requirements validation should be undertaken by cross-functional teams.
- Gaps need to be identified, even if they cannot be filled, especially for interfaces, new technology or cost drivers [19]. Downstream changes can then be anticipated.
- Configuration control of requirements must be fit-for-purpose for iterative agile development in a model-centric environment (see MBSE, **Section 3.3**).
- The number of requirements should be minimised, with focus on a core set of cardinal requirements that can be validated and stabilised quickly. More concise requirements leave more space for design flexibility, reduce the verification burden and increase collaborative working between teams.
- Assumptions need to be consistently captured and communicated in the same way as formal requirements to avoid divergence and downstream rework.

Verification

In structured verification, every requirement is aligned to one or more planned verification activity specifically intended to show product compliance with that requirement. This drives the verification and validation (V&V) efforts only towards those activities that are needed for a customer or regulator to accept or approve the system.

Aerospace has been trending towards ever increasing reliance on simulation for the past 50 years, reinforced by established data sets and validated models for iterative technology. As simulations have improved, they have become the primary means of verification whilst testing has increasingly become a validation of the model or a confirmatory check rather than a means of learning in itself.

Increasing computational power and tool fidelity, combined with improvements in data post-processing and visualisation, means simulation will continue to be a primary verification tool for complex systems, providing engineers with greater insights to design behaviour than previously possible (see **Section 3.3**). This will enable greater understanding and speed of interpretation of results and can help to avoid the need for some confirmatory testing entirely [20]. Over time, this trend will increase the feasibility of greater use of certification by simulation instead of test to accelerate entry into service [21] (see also **Certification** below).

However, a focus on simulation has led to a hesitancy towards early testing and a fear of test failures (if the test does not prove the simulation, that becomes seen as a failure of the test). However, models and simulation are still abstractions of the real world, and the tipping point between simulation and testing will not be constant. Critical thinking needs to be applied to what information is actually needed when determining verification methods for each activity to deliver that information as quickly as possible – especially in areas of high uncertainty.

Compressed V&V enablers include:

- Fail-fast, learn early tests provide key learning opportunities, regardless of outcome.
- Reuse of existing test equipment to learn about new technologies (e.g., adapting kerosene combustion test rigs for liquid hydrogen) can help generate useful early data – especially for critical path technologies.
- The revolutionary technology needed for a zero carbon-emissions aircraft means that existing datasets will have gaps, so new data needs to be generated via testing (e.g., materials data, cryogenic thermo-fluids data, hydrogen combustion).
- The volume of iterative verification activities can be streamlined using a design of experiments (DOE) approach to optimise the factors being varied between iterations.

Certification

The unique architectures and technologies in a zero-carbon emission aircraft will present challenges for regulators and certification teams. FlyZero has been working with the UK Civil Aviation Authority (CAA) to identify specific areas of the CS-25 (Large Aeroplanes) certification requirements which present differences for a liquid hydrogen-fuelled aircraft. These have identified four certification challenge topics: liquid hydrogen fuel system, crashworthiness, hydrogen explosion prevention and environmental protection **[22]**.

It is reasonable to anticipate that any airworthiness regulator will take a conservative view towards the certification of new technologies where there is little design heritage. Strong, linked-up evidentiary trails of design decisions and supporting data based on experimental testing and simulation need to be maintained. Industry needs to both challenge itself to a high internal standard of validation and include regulators on that journey of validation through the development programme to mitigate late-project issues and delays.

An international regulator working group (e.g., led by or including the Aviation Rulemaking Advisory Committee) involving the main airworthiness regulating bodies, is essential to ensure the consistent understanding and application of new or existing rules to liquid hydrogen aircraft.

Test Infrastructure and Flying Test Bed

Global experience with using liquid (as opposed to gaseous) hydrogen as a working fluid is at a low level across any industry sector, with experience on a limited number of programmes in the space sector. Development of test facilities for liquid hydrogen is the critical path to enable system component testing for a zero-carbon emission aircraft. This needs to be accelerated as a ring-fenced priority to support a necessary fail-fast, learn early approach to reduce uncertainty and increase working knowledge in those technologies. Establishing a national hydrogen test centre should be considered, to group fuel system and engine rigs together for synergies in fuel supply and skills development in conjunction with other industries already or potentially working with cryogenic liquid hydrogen (e.g. energy, space, heavy automotive and marine) [23].

The level of new technology required for a zero-carbon emission aircraft will also require a flying test bed (FTB) campaign to sufficiently validate the performance and design assumptions of the cryogenic liquid hydrogen tanks, fuel system, thermal management system and hydrogen gas turbines in a working airborne environment. This is typically not required for legacy aircraft systems (with engines being a common exception). Without the FTB stage, an unacceptably high level of uncertainty in those technologies would be carried forward to the production aircraft design, where design changes are significantly more difficult to make.

For compressed design and validation, this effectively means that the fastest route to an in-service production aircraft must go via a flying test bed design of each new technology first, with allowance for a significant amount of design change between the two designs (FTB-standard and production-standard) of each affected system. This would not apply to the more evolutionary and iterative elements of a zero-carbon emission aircraft, which could be designed once for the production standard (see Figure 6).

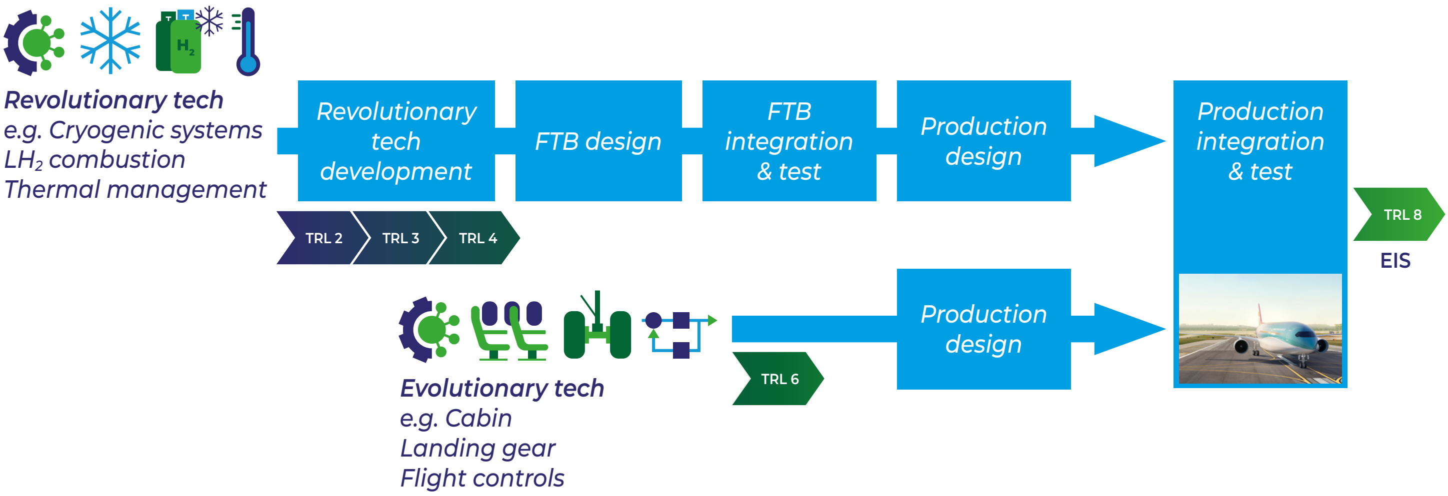


Figure 6 – Development path for new technology via a flying test bed design standard, and evolutionary technology direct to production standard

03. ENABLING TECHNOLOGIES AND TOOLS

This section will cover the theme of emerging technologies and tools that offer opportunities to compress development time scales, with a focus on digital tools. In addition to industrial interviews and research, this section also heavily draws on the FlyZero offload work package findings by CFMS [24]. Figure 7 below shows a summary of the section on technology and tools opportunities.

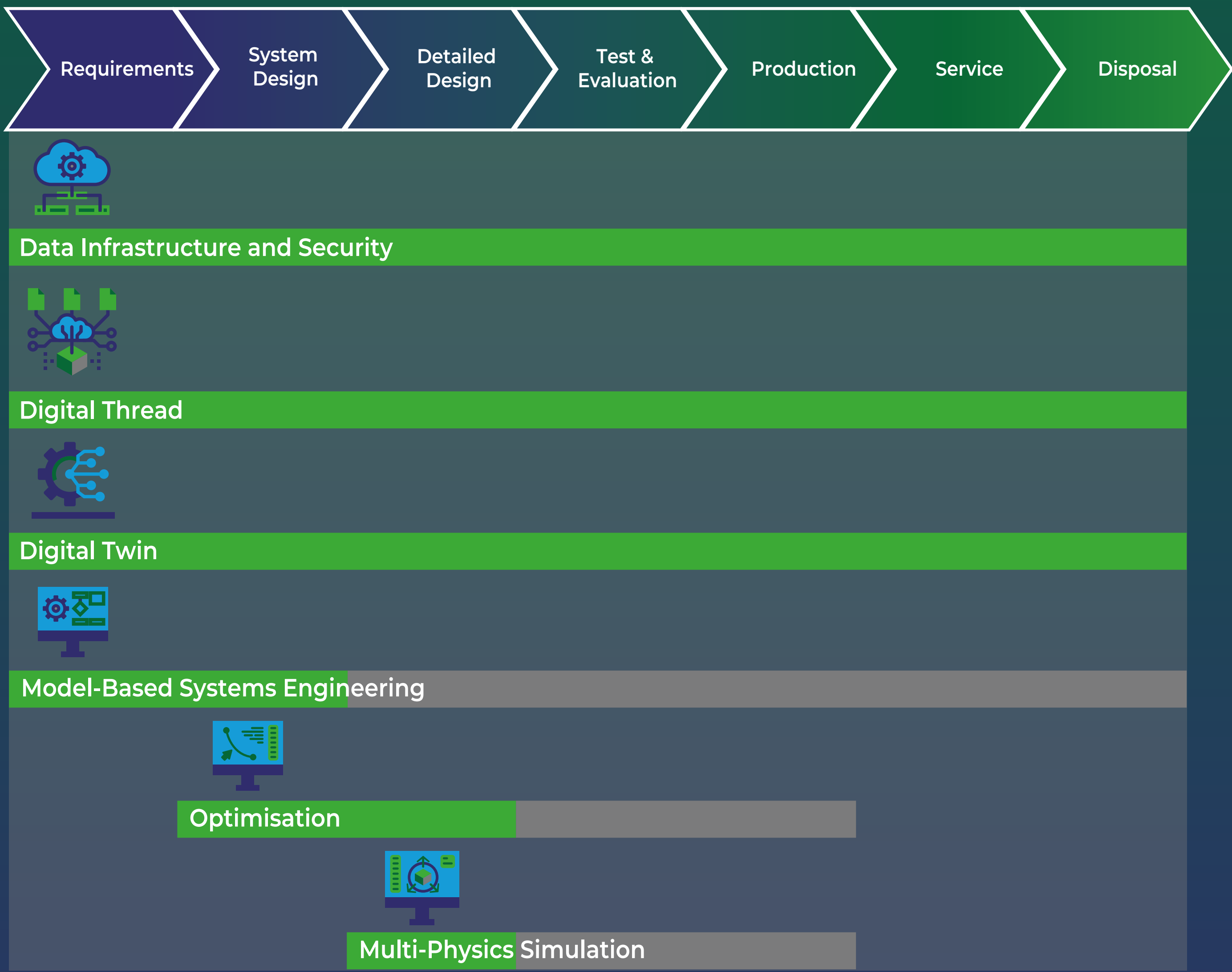
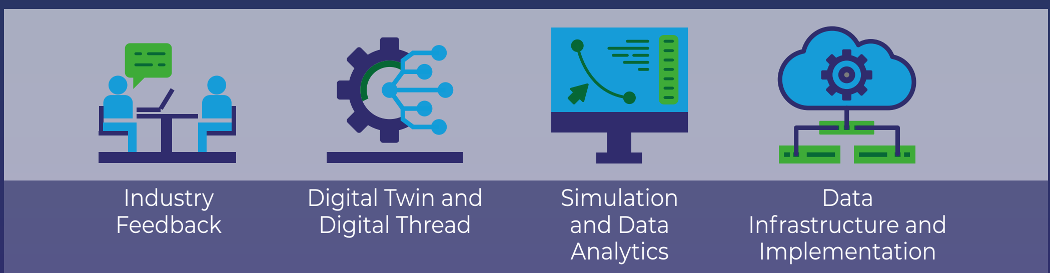


Figure 7 – Application of technology and tools opportunities within the product lifecycle

This section will look at opportunities grouped as follows:

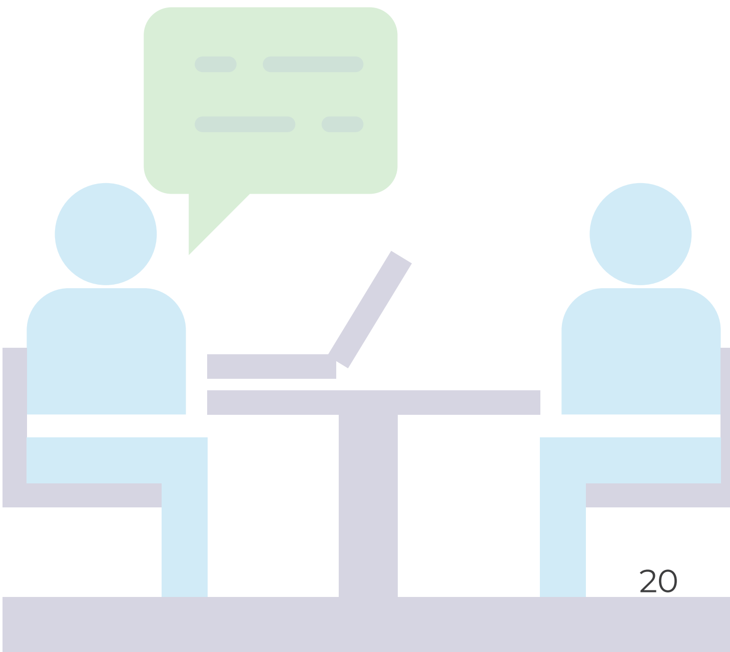


03.1
INDUSTRY FEEDBACK

Our interviews with existing industrial organisations on the topic of technology and tools suggested that many of the elements discussed in this section are still in nascent state, if adopted at all. The larger aerospace integrators are generally further progressed on digitalisation than smaller ones or suppliers. Work to combine model-based engineering (MBE) tools into a joined-up multi-physics and multi-domain tool suite, such as Dassault Systèmes 3DEXPERIENCE (3DX) or Siemens NX/TeamCenter are being adopted in some project areas (e.g. Airbus has been implementing their digital design, manufacturing and services (DDMS) environment using 3DX **[25]**). Similarly, elements of design optimisations are undertaken, but not yet brought together into the holistic and automated approach described in this paper.

Model-based systems engineering (MBSE) has been making inroads into new systems development but is still relatively under-utilised outside of a systems engineering core. Companies are also now starting to bring broad-scope MBSE and narrow-scope MBE models together into digital twins.

Although the benefits of digitalisation are generally recognised, the main challenges to wider adoption of digitalisation cited include the cost of IT tools and infrastructure investment, the cost of compiling data for model validation and barriers in data security and control.



03.2
DIGITAL TWIN AND DIGITAL THREAD

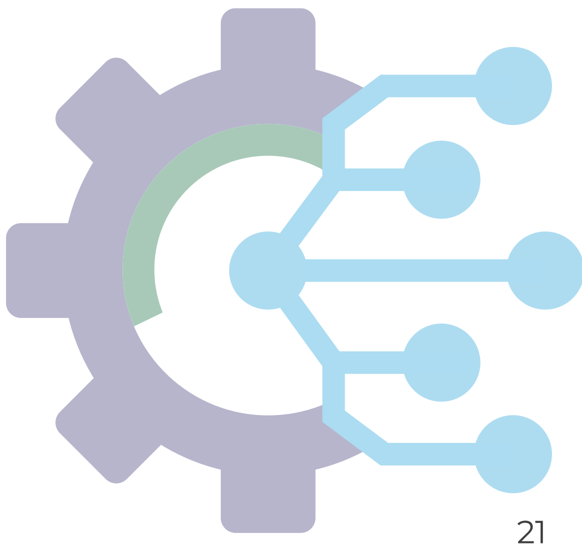
A digital twin is a model of a real physical product (an aircraft, an engine, a component), as opposed to a design (a model of the nominal product). The digital twin is 'live' and so represents the state of the product at that point in time. There are bi-directional information linkages that enable feedback between the digital and physical worlds, enabling live decision making but also for the data to be used to improve simulation and analysis.

A digital thread is a common dataset for a specific physical product that captures all information that is considered important enough to retain, including historic data. The digital thread might therefore contain past instances (snapshots) of the digital twin, covering the entire lifecycle of that product. The digital thread would act as the primary data source for that specific physical product.

There is a technology trend towards creating digital twins that comprise a series of interconnected models from both system level (MBSE) and subsystem / component level (MBE), enabling both the full scope to of the system to be covered and fidelity.

The interoperability of data must be addressed for the digital twin and thread to become useful; it must be possible to automatically extract and use necessary information from seemingly disparate data sources and formats, and for that information to be widely accessible to form a common data environment (CDE).

Combining the data from the digital thread for all products of the same type (part number, module number or engine type) can create a powerful dataset upon which analytics (e.g., simulation or machine learning) can be used to derive new knowledge. During development, this knowledge can help drive future iterations of a product design or manufacturing process. During service, this dataset can be added to with data from sensors monitoring the component to predict life and maintenance intervals or feed information back to support design improvements. Figure 8 shows potential use cases of the digital twin during the different lifecycle phases.



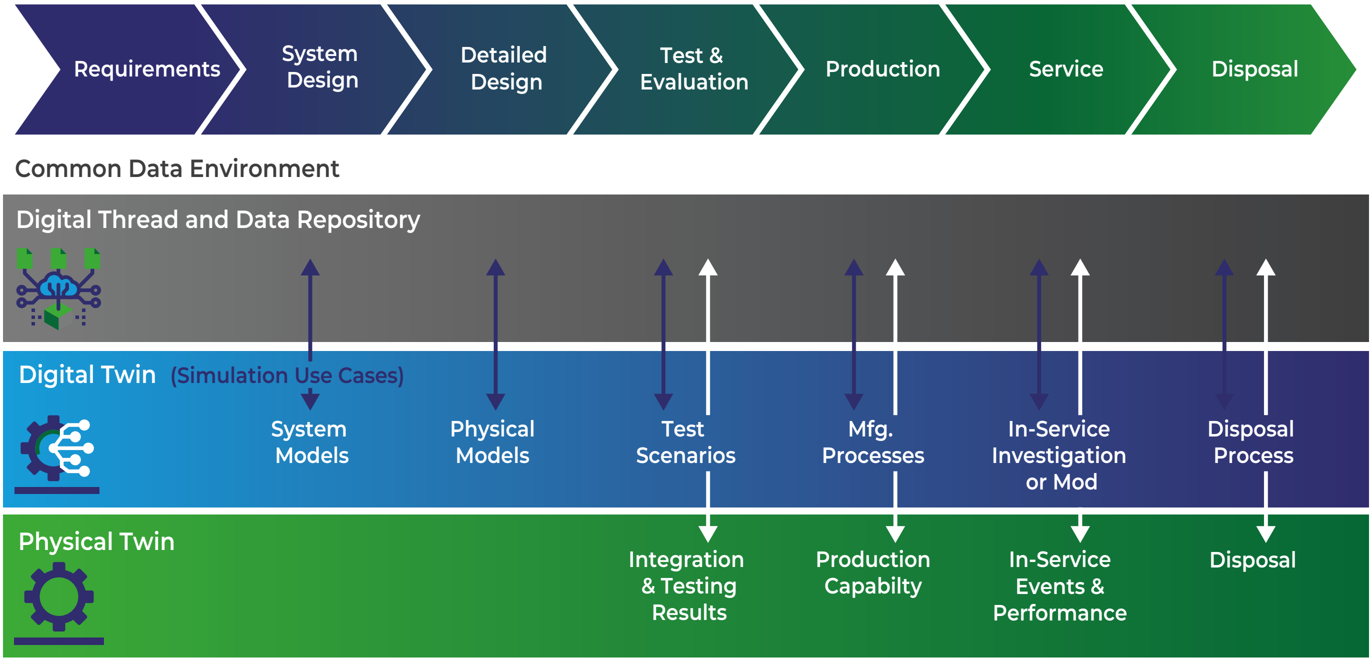


Figure 8 – Simulation uses cases of the digital twin and thread throughout the product lifecycle

Both digital twin and digital thread architectures need to be available to start populating from day one of a project so that all engineering work, from requirements onwards, can begin in a model-centric fashion.

Case Study 4 – DRAMA – digital twin and digital thread for additive manufacturing

DRAMA was a UK aerospace supply chain project led by the National Centre for Additive Manufacturing at MTC, funded by UK Research and Innovation (UKRI) as part of the Industrial Strategy Challenge Fund and supported by the Aerospace Technology Institute.

A major activity in the project was to build the UK's first digitally twinned additive manufacturing facility, with 'twinning' at both the process level and at the facility level and connecting with numerous machines covering multiple process stages (design, print, post-processing). The project created an architecture which enabled the easy integration of digital tools (CAD models, analytics and simulation) – both commercial tools from different vendors but also tools developed by the MTC. This was enabled by using a 'hub and spoke' architecture with a 'data lake' at its core. All the data associated with the digital thread for every component and process is stored in the data lake but with a security system that allows only authorised people and projects to access it. The raw process data is parsed to extract key parameters in a common comparable format. New knowledge about the processes and designs could then be generated by running analytics on the data lake, both on recent data and historic data. Using a data engineering workflow management solution, analytics (including new simulations, statistical analysis, machine learning, etc.) can be run relatively easily on the data lake.

Through this project, MTC demonstrated how modern digital architectures can enable a more powerful digital twin. Industry and research projects should consider related solutions to enable more rapid development of new products and manufacturing processes.

03.3 SIMULATION AND DATA ANALYTICS

Simulation and data analytics cover digital modelling tools which can bring acceleration opportunities in model-based systems engineering (MBSE), multi-physics simulation and optimisation tools.

Model-Based Systems Engineering (MBSE)

MBSE refers to the application of systems engineering using tools and techniques to model, simulate and communicate a functional system in a prescribed way. Example tools include Cameo, Capella and Enterprise Architect. The model also includes interacting and supporting elements, such as requirements and verification, stakeholders and the operating environment, so is used throughout the lifecycle [26] (see Figure 9).

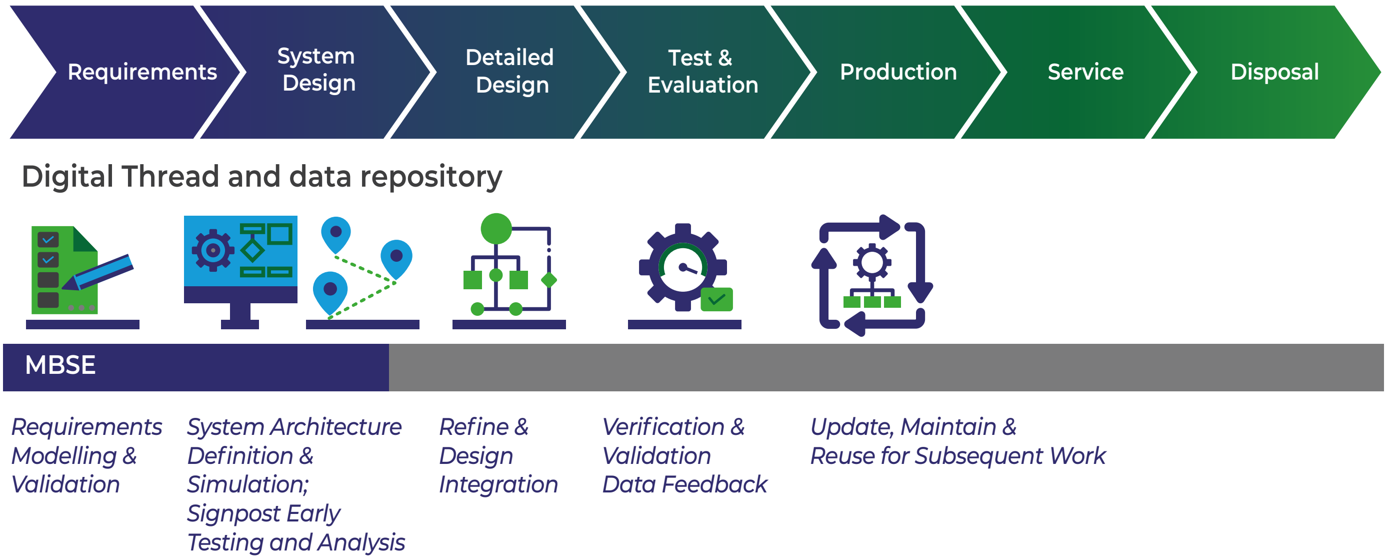


Figure 9 – MBSE use cases throughout the product lifecycle

MBSE allows system behaviour to be simulated and provides a clear definition of functional interfaces between system elements. This enables the identification of emergent properties, conflicts and dependencies as well as requirements validation through simulation and functional traceability [27]. Models can be front loaded with previously document-based data (e.g., requirements [28]), enabling a shift to fully model-centric engineering. Thus, model viewpoints become a primary means of communicating system information, enabling faster collaboration, technical review and decisions.

Optimisation

Multi-objective optimisation (MOO) is used to find an optimum balance of key design requirements through analysis of how multiple parameters influence, compete with or support each other in the overall design. Thus, a suitable trade-off between them may be required to achieve an optimum performance for the overall system. This is potentially applicable to almost any system within the aircraft. Tools include iSIGHT, NIMBUS, HEEDS and Autodesk Fusion 360. Both data analytics and machine learning could be used in high-speed automation of the parametric analysis; research into this includes the ATI and Innovate UK co-funded COLIBRI project to explore and develop new tools that exploit machine learning to improve and speed up the collaborative design [29] and Innovate UK-funded AI-AHEAD project investigating the use of machine learning to accelerate heat exchanger design [30].

MOO can accelerate design space optimisation, providing a faster path to an optimised design configuration (see Figure 10), and help to avoid undesirable design points that could lead to rework or time-consuming testing. This can be applied at system and sub-system level and be expanded to multi-domain optimisation to take account of other factors (e.g., weight, lead times, manufacturing cost).

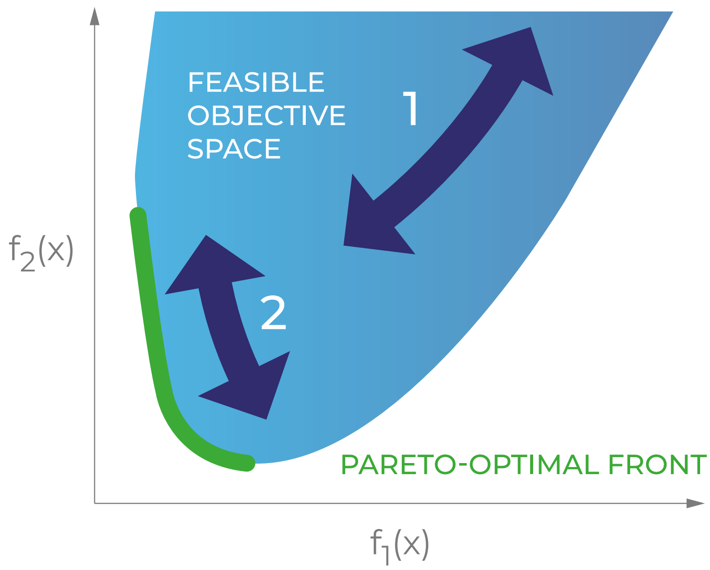


Figure 10 – Using MOO to identify optimal solutions (along a pareto-optimal front) from a large and diverse a set of feasible objectives

Simulation and Uncertainty Quantification

Multi-physics simulation is a branch of model-based engineering (MBE) that allows engineers to assess behaviours and interactions between multiple physical domains within a single tool or directly coupled tools, e.g., in the thermal management system, fuel cells and liquid hydrogen storage. This eliminates the need for convergent iteration between separate discreet simulations in a 'toolchain', accelerating the simulation process and providing a potentially higher degree of optimisation depending on the fidelity of assumptions. Example tools include elements within Dassault Systèmes 3DX and Siemens NX/Teamcenter, as well as COMSOL Multiphysics, MOOSE and CREATE (which was developed with US Department of Defense support to improve the accuracy of the complex weapon performance predictions and greatly reduce their time to market **[31, 32]**).

Simulation tools for domains associated with new technology (e.g., cryogenic modelling tools suited for aerospace to predict hydrogen properties and states, and modelling of aerodynamics and multi-scale heat exchanger flow fields) will also need to be developed and validated (see also **Democratised Simulation and Intellectual Property Drift** below).

The ATI modelling and simulation working group discussed that managing uncertainty in simulations is a challenge in the following areas: propagation of uncertainties when scaling from micro to macro level and incorporating uncertainties in failure models from manufacturing to analysis.

Finally, further advances in simulation and visualisation capability need to keep pace with technology or the process of digitalisation will stagnate, such as improved scalability **[33]**.

Democratised Data

More advanced forms of analytics for the tools described here require larger amounts of validated data. This data needs to be built up with increasing fidelity levels within the digital twin / digital thread from more basic simulation and from testing.

These tools can be developed out-of-cycle (i.e., conducted prior to launch of a production programme) using generic design features, manufacturing processes and materials data to create a minimum viable data set, and continue to be updated and improved over time and would be reusable in subsequent projects.

Democratisation of real-world data is urgently needed to mitigate the cost of access to validated data sets across the supply chain. This requires data that is freely available across many organisations. UK public funding bodies can support this by funding development of publicly owned unbiased testing data for model and tool validation, especially in areas with little existing data (e.g., liquid hydrogen behaviour, impact of liquid hydrogen on material properties and microstructures) and where similar datasets can support many applications. Precedent exists, such as in US academia and research organisations (e.g. **[34, 35]**), the EU Online Data & Information Network for Energy (ODIN) **[36]**, and the UKRI-funded UK Data Service **[37]**. To keep such activities manageable, smaller specialised datasets or simulation-generated datasets should be prioritised.

Democratised Simulation and Intellectual Property Drift

Evolutionary product iteration within aerospace has led to a high degree of embeddedness of specific tools with proprietary formats. This can leave organisations somewhat locked-in to certain vendors and tools, impeding the adoption of new or open-source tools. Greater tool complexity and integration within single-vendor ecosystems have the potential to erode democratised simulation – the flexibility of design organisations to modify these tools to include their own functions, design rules or validated data sets.

As all models will interact within a digital twin, it is important that models at every level are synchronised and managed consistently within harmonised frameworks, ontologies and standards to avoid conflicting assumptions or parameters between individual models. Such standardisation efforts should seek to align with similar efforts elsewhere, e.g. American Society of Mechanical Engineers (ASME) MBE Standards Committee **[38]**, the National Institute of Standards and Technology (NIST) **[39]** and The Open Group **[40]**.

As more intellectual property (IP) becomes locked into the tools themselves, there is a risk that over time, the ownership of IP will drift from the design organisations to the tool developers. Despite the excellence in UK academic research, the vast majority of digital tools used within aerospace are developed by non-UK companies (see **Figure 11**), leaving UK industry at an overall disadvantage.

The current disruption in technology creates new opportunities for UK tool developers to break through, with the hope of gaining increased market share in future. Tool opportunities include the modelling of liquid hydrogen behaviour and materials behaviour in liquid hydrogen environments. These tool gaps need to be closed to achieve a liquid hydrogen-fuelled aircraft in the desired timescales. Such tools will require public research and development (R&D) funding and would benefit from strong central coordination and steering to interface with industry for validation and widespread adoption.

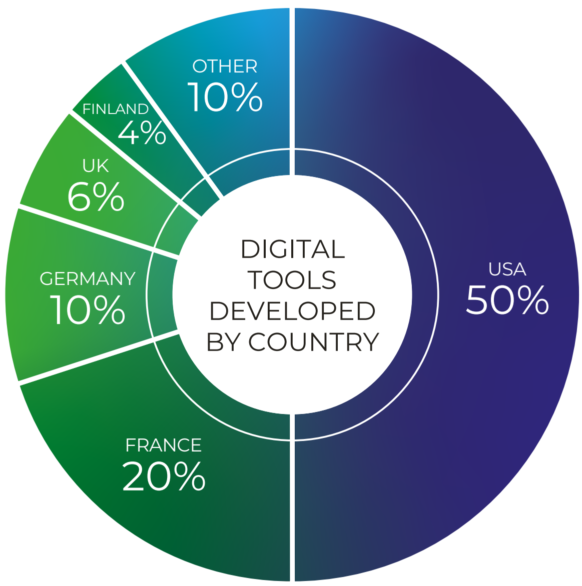


Figure 11 – Digital tools developed by country (based on CFMS offload package for FlyZero)

03.4 DATA INFRASTRUCTURE AND IMPLEMENTATION

Collaborative Infrastructure

Large integrated models of high fidelity e.g., 3D CFD simulation of hydrogen combustion to integrate multi-physics domains, will drive a need for ever higher computational processing performance, to the petaflop (10^{15} flops) scale and even exaflop (10^{18} flops) scale [33, 41]. The application of high-performance computing (HPC), edge solutions or hybrid cloud solutions working in a common data environment (CDE) provides solutions that can be shared or contracted as required, avoiding heavy up-front investment or continuous maintenance (see **Case Study 5** below). Research into digital-enabled collaboration includes the ATI-funded APROCONE [42] and COLIBRI [29] projects.

Heavy collaboration and information sharing between organisations will be necessary throughout all phases of design and validation, with ready access to data and processing power fundamental to delivery. Secure CDEs provide a central and collaborative data capability to distributed personnel. The scale of dependency on shared digital resources will benefit from greater automation in underlying IT tools and services to streamline access to software, problem set up and the management of data.

Other considerations in establishing a collaborative environment include common standard interfaces, complex simulation orchestration and model interdependency management.

Case Study 5 – CFMS High Performance Computing (HPC)

The CFMS data centre includes multiple on-premises HPC clusters and secure clouds to support commercial and open-source applications, providing scalable platforms for differing applications in aerospace and other sectors. These capabilities provided secure HPC access to simulate wind turbine performance for energy production optimisation. The simulation results were also produced in two days, compared to three months for previous calculations.

CFMS have also used their secure HPC environment to rapidly evaluate a range of propulsion options for more sustainable sub-regional aviation in the Scottish Highlands and Islands on behalf of the Scottish Government. The outcomes have helped influence government policy with regard to the timing of decarbonisation for this essential mode of transport for isolated communities.

Implementation and Cost

Culturally, successful digitalisation requires having senior leaders on board, building new skills and capabilities in the workforce, empowering people to work in new ways and frequently communicating progress and benefits **[43]**. See also ATI FlyZero 'Workforce to Deliver Liquid Hydrogen Powered Aircraft' **[44]** on addressing skills development.

The cost of digitalisation poses a major barrier, especially to lower tiers of the supply chain. The promise of increased value from these tools can be eroded by large scale licensing, operating and maintenance costs, and waste through miscoordination. To manage this:

- OEMs need to provide clear direction and support to their supply chains to ensure consistent and synchronised adoption.
- Organisations can coordinate adoption of shared or chained-together assets, or work with a central computational service provider to reduce up-front investment.
- OEMs can make their digital assets available to contracted suppliers to maximise their utilisation – this approach would even be preferred for collaborative working.
- Long-term data costs are minimised by maintaining only what is likely needed for downstream activities to support design, investigations and compliance traceability.

Data Ownership and Security

The high degree of connectivity of digital twins and digital threads presents a challenge of how to manage access to sensitive data while keeping the tool useful in multiorganisation or multinational partnerships. Within a single project or supply chain relationship, enabling sharing through licences and contractual agreements is preferential to eliminate barriers to collaboration. Clear ownership rules and constraints of data and IP produced needs to be addressed through commercial frameworks and technical processes [42]. Data security requirements need to be defined very early so the digital thread architecture can still optimise overall functionality with the necessary interfaces between different data sets [45].

Protection of IP and compliance with export control regulations have led to an increased use of secure data services which have known locations for the underlying infrastructure used to store, transfer and maintain that sensitive data.

Obsolescence

Digital twins and the digital threads behind them will need to be utilised or accessed over the full operational lifecycle of an aircraft (30+ years). This means that obsolescence in the model and its supporting IT infrastructure cannot realistically be avoided.

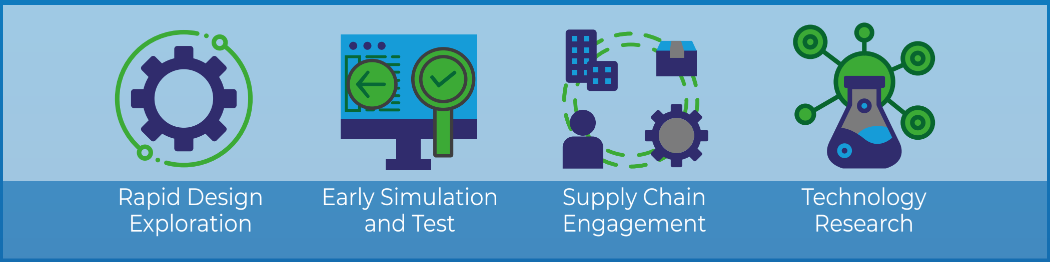
Moving to a major vendor standardised toolsets will provide some degree of insurance against obsolescence but at a cost and with risk of lock-in. Alternatively, the architecture of the digital thread and digital twin itself can be designed to move likely points of obsolescence to a lower level of the architecture which can be managed with software that is more generic (not specific to engineering). These will be more flexible and could be cheaper to maintain and update over time.

Sustainability

High-power computing and mass data storage consume large amounts of energy. Their carbon impact is not negligible and needs to be considered. Improvements in energy-efficient computing for engineering tools and fixed server IT systems, as well as growing electronics waste, have not been prioritised in industry [46]. Organisations can help improve this by promoting sustainability and net-zero targets when procuring or specifying IT services and tools. Also, the use of digital threads can also help minimise unnecessary duplication of raw data storage, in combination with optimising what data needs to be maintained to support future lifecycle phases or reuse.

04. BRINGING ELEMENTS TOGETHER

As discussed in **Sections 2** and **3**, the challenges of compressed design and validation require an organisation-wide, multi-thread approach across both culture and technology. Although powerful in themselves, we can also link some of those elements together under a few key themes to accelerate design and validation:



04.1 RAPID DESIGN EXPLOITATION

Rapid design exploration can be applied at both the system level with model-based systems engineering (MBSE) and lower levels with model-based engineering (MBE). Combining these parametrised models with multi-objective optimisation (MOO) and multi-domain, multi-objective optimisation (MDMOO) allows engineers to quickly assess the design space to identify an optimal configuration. The use of genetic algorithms or a DOE approach can apply a more efficient partial-factorial analysis across all parameters and evaluate where the optimum points and areas of instability lie.

Rapid design is suited to an iterative agile approach. Knowledge is gained through each loop and directly incorporated into the design through the MBSE and MBE models in the digital twin for the next iteration.

Automated design optimisation is dependent on a sufficiently large data set facilitated by a digital thread. To realise the greatest benefit, the iterative analysis needs to be executed with the use of machine learning or data analytics to cover a wide breadth of potential design points as quickly as possible. Assessing as wide a space as possible will reduce the risk of downstream change and rework during detailed design, as well as supporting the best overall design.

Rapid design should be combined with existing methodologies that proactively prevent downstream quality or performance issues, such as design for six sigma (DFSS) **[47]** and design for excellence (DFX) (including design for manufacture, design for reliability, etc) **[48]**. Such preventative approaches are well suited to new technologies which have little existing design heritage, by anticipating quality, compliance or cost driving issues before they emerge in integration or production. Early understanding of the relationships between design inputs and outputs enables a design to be optimised to meet a target with reduced variability, validating the outcomes of rapid design optimisation.

04.2
EARLY SIMULATION AND TEST — LEFT-SHIFTING VERIFICATION AND VALIDATION

The concept of left-shifting verification and validation (V&V) is to bring forwards in time as many V&V activities as possible. This reduces the risk of late rework or delay during the testing phase. Left-shifting V&V can be managed through a structured verification approach to ensure that only necessary V&V activities are undertaken, with appropriate use of modelling, simulation and the digital twin (see **Figure 12**).

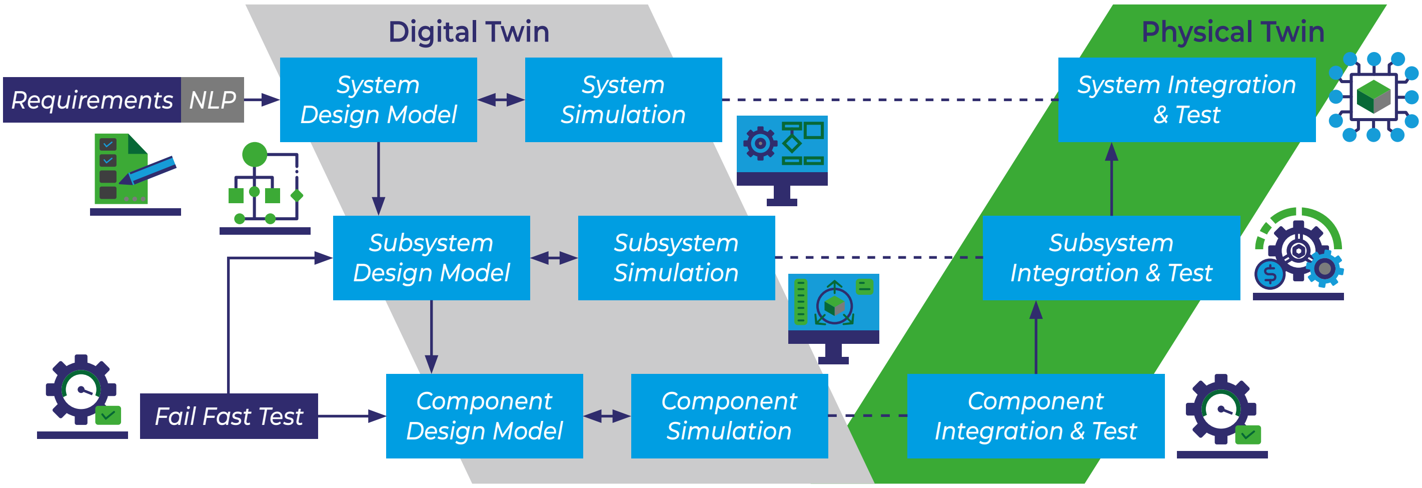


Figure 12 – Left-shifting V&V with simulation in the digital twin

A structured V&V plan needs to focus on showing compliance against requirements. Using MBSE and a natural language processing (NLP) machine learning model, the requirements are rapidly populated or changed in near-real time. MBSE then allows the early functional behaviour of the system to be simulated and assessed to confirm assumptions and interfaces for lower-level design, allowing better optimisation for integration and definition of interfaces. The MBSE models also help to identify knowledge gaps or risks in system behaviour, providing a roadmap for early testing requirements.

All modelling and simulation activities can be integrated to cover the entire system and linked at multiple levels to the real system to create a digital twin. The digital twin enables engineers to rapidly and accurately assess or even outright replace various physical test scenarios defined in the structured verification plan, with the digital thread providing an effective means of data traceability and auditing to reduce the preparation or reporting effort for individual verification activities. Multi-physics simulation tools where appropriate for lower-level design elements will reduce the length of a modelling "tool chain", enabling designs to be verified more quickly with few model iterations between tools.

Early small-scale physical testing remains important to de-risk areas of new technology. For hydrogen-powered aircraft, there are areas where there is very limited availability of design data or validated models. Examples include early integration testing of fuel system components / units, cryogenic tank testing and liquid hydrogen behaviour and handling. A fail-fast and learn early approach is necessary to test key technology drivers to confirm their feasibility for use in the wider system.

Case Study 6 – SpaceX

SpaceX became the first commercial company to operate reusable rockets to deliver supplies to the International Space Station and to carry NASA astronauts into orbit, leap-frogging much of the aerospace establishment in the process. These accomplishments were delivered in part thanks to an agile approach coupled with rapid decision making. SpaceX also embraced a fail-fast, learn early culture, while simultaneously investing in the automation of designing and validating through simulation [17], [49].

04.3 SUPPLY CHAIN ENGAGEMENT

The interface between a customer and supplier can at times serve as a barrier to communication, data sharing and visibility within a development programme and is a root cause of delay and rework. These can be resolved by changes in cultural approach and an increase in digital collaboration and enabled through associated changes in the supply chain engagement business models, including:

Scope and Requirements

- Select, engage and ramp-up suppliers early so they are ready as soon as the requirements are released to avoid knock-on delays.
- Clear, concise and validated scope and requirements covering all deliverables (product, project and documentation) help avoid delay or rework. Any unknowns need to be explicitly addressed with placeholders and working assumptions.

Digital Integration

- Co-development and sharing of model-centric requirements, simulations, digital twins and the digital thread. Configuration control and management must be fit for purpose for such a rapidly changing agile and collaborative working environment.

Trust and Delegation

- High levels of trust, built up through close cooperation and frequent liaison, minimise misunderstanding and promote more efficient problem solving.
- Joint risk management sessions provide a transparent forum to share knowledge for the benefit of the project. Micromanagement must be avoided.
- A supplier should be delegated all design decisions and verification activities within their scope and requirements, on the basis that they know their product and processes best, so can make decisions to enable the most efficient delivery. This is facilitated by consistent definition of supplier functional interfaces within MBSE.

04.4 TECHNOLOGY RESEARCH

Different phases of development are often carried out in separate departments or organisations, across industry, research organisations and academia. Acceleration requires effective handshakes, which could be facilitated by:

- Increased direct collaboration between industry and academia for new technologies where knowledge and facilities are decentralised across several organisations and institutions (e.g. hydrogen combustion).
- Use of multi-functional project teams in R&D projects that include experience from across organisations and across the product lifecycle.
- Use of a joint TRL gate process across organisations and technologies to ensure common progress of all technologies required for a zero-carbon emissions aircraft.
- Both R&D and production projects must work in the same model-centric data environment, ideally in a continuous digital twin from the start, to maintain continuity and traceability of knowledge and data as technologies mature.

05. RECOMMENDATIONS AND KEY CONSIDERATIONS FOR INDUSTRY

FlyZero has concluded that the entry into service date of large (narrowbody and midsize) commercial hydrogen powered aircraft is the factor that will most affect the global aviation sector's contribution to carbon dioxide emissions – the earlier the entry into service the lower the carbon dioxide emissions.

In addition, UK companies can maximise their share of these future aircraft by being first to mature these key technologies. The challenges of bringing such a revolutionary commercial aircraft design to market are significant. To accelerate this development will require an immense effort from the aerospace supply chain, research bodies and governments.

Section 5.1 section lays out recommendations for specific actions that the UK aerospace community can take to accelerate technology development. **Section 5.2** lists some considerations for industry - the next steps on their journey to compress the timeline for design and validation.

05.1 RECOMMENDATIONS

The recommendations for action that the UK aerospace community can take to accelerate technology development are listed below. These recommendations are directed to the whole UK aerospace community, including industry, trade bodies, research, academia, the Aerospace Technology Institute (ATI) and UK Research Innovation (UKRI).

Promote adoption of more a more agile culture by the aerospace sector.

- The UK aerospace community should push the need for a more agile culture to accelerate the development of radical new technologies up the agenda, aiming to raise the issue to executive level and providing forums for solutions.
- Research projects could consider more agile approaches. Funding bodies like the ATI and UKRI could encourage the adoption of agile approaches in the projects that they fund, particularly for those relevant to compressed design and validation.

Enable access to digitalisation resource and new tools within the UK supply chain.

- The UK research community should coordinate national level computing resources and infrastructure, to enable cost-effective access by all levels of industry for simulation of heavily integrated, multi-level or multi-domain models linked into real assets (test rigs, process lines, products) to form digital twins.
- UK research funding should be directed to the development of new digital tools to address current and future technology gaps. A formal gap analysis needs to be conducted to identify digital tools required for the development of hydrogen aircraft and bring forward research programmes to address these gaps.

Coordinate modelling frameworks across industry to streamline collaborative working between teams and organisations and enable greater tool diversity.

- A research programme should be launched in partnership with international standards organisations to bring forward a harmonised set of modelling frameworks, standards and ontologies to be used across aerospace and research partners to facilitate collaborative model interpretation and sharing.

Champion the democratisation of data to support early model and tool validation.

- Some datasets will enable innovation across many aerospace and research organisations. These datasets should be identified and generated for the use of the whole of the UK supply chain, to support the validation of models and tools funding (e.g. liquid hydrogen behaviour, impact of liquid hydrogen on material properties and microstructures). An organisation should be identified to own and manage access to these datasets.

Progress critical liquid hydrogen test infrastructure at a national scale to support necessary technology characterisation and systems integration testing.

- A ring-fenced programme is needed to plan and create a national-level, open-access test facility for integrated liquid hydrogen systems. The ATI is well positioned to support this, possibly in joint-funding collaboration with other sectors (e.g., energy, space, marine) for shared testing requirements.

Encourage progressive cooperation with regulatory authorities on the path to certification for hydrogen-fuelled aircraft.

- Industry bodies (including the ATI) can support by hosting forums to promote close cooperation between regulators and industry to facilitate knowledge sharing on maturing technologies and to encourage an international working group between regulators to develop consistent approaches to rules and compliance.

05.2 KEY CONSIDERATIONS FOR INDUSTRY ORGANISATIONS

Considerations for industry working to compress the timeline for design and validation are as follows:

- **Embed efficient design and validation good practices** such as design for excellence (including design for manufacture, design for reliability), design for six sigma and design of experiments to avoid unnecessary scope and rework.
- **Shift the organisation to a more agile culture** with leadership support and necessary investment in training and organisational change.
- **Formulate a digitalisation strategy** to enable collaboration in a digital twin/digital thread engineering environment. Define and implement strategies to achieve the required use cases across the supply chain and product lifecycle, considering the necessary tools, training and infrastructure including connectivity and the long-term data needs.
- **Adopt an end-to-end model-centric (MBSE, MBE), data-driven approach** to optimise design and validation activities. In doing this, companies must plan for how tools can evolve to keep pace with progressive demands from technology and design. They must increase the knowledge level in data analytics and data engineering.
- **Embrace early testing and simulation** to manage uncertainty and data gaps. Companies should identify knowledge and data gaps and fund testing early.
- **Progress critical test infrastructure for liquid hydrogen systems**. Collaborate within industry to confirm requirements for new central facilities. Increase collaboration on shared test facilities and reuse of existing equipment to jump-start test campaigns.
- **Prepare early groundwork for certification**, especially around the certification challenge topics: liquid hydrogen fuel system, crashworthiness, hydrogen explosion prevention and environmental protection. Take advantage of a model-centric engineering environment to capture and maintain comprehensive and traceable evidentiary trails for regulators in the digital thread.

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06.1
TABLE OF FIGURES

06.2
LIST OF ABBREVIATIONS

3DX — *3DEXPERIENCE*
ASME — *American Society of Mechanical Engineers*
CFD — *Computation Fluid Dynamics*
EIS — *Entry Into Service*
DDMS — *Digital Design, Manufacturing and Services*
DFSS — *Design for Six Sigma*
DFX — *Design for Excellence*
DOE — *Design of Experiments*
FTB — *Flying Test Bed*
HPC — *High Performance Computing*
IP — *Intellectual Property*
LH_2 — *Liquid Hydrogen*
MBE — *Model-Based Engineering*
MBSE — *Model-Based Systems Engineering*
MTC — *Manufacturing Technology Catapult*
NLP — *Natural Language Processor*
OEM — *Original Equipment Manufacturer*
TRL — *Technology Readiness Level*
MDMOO — *Multi Domain, Multi Objective Optimisation*
MOO — *Multi Objective Optimisation*
MPS — *Multi Physics Simulation*
R&D — *Research and Development*
SAFe — *Scalable Agile Framework*
UKRI — *UK Research and Innovation*
V&V — *Verification and Validation*

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