European Consortium For the Advanced Training in Aerospace

Simple and Robust Aircraft: Challenging the Trend of Increasing Complexity

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ABSTRACT: Complexity within the aerospace industry has become a general cause to blame for increased development costs and products with delayed entry into service of military aircraft during the last decades. Staying ahead of the competition, reducing cost and time-to-market are the most important factors to improve, as well as availability and reliability of an aircraft. Complexity affects all the above and therefore the negative effects of it must be reduced. Looking at complexity more closely, it comes from several different drivers and affects various areas simultaneously making it hard to understand. Complexity is very subjective by nature and depending on the topic of interest, it can take many different forms and definitions. Complexity is an indicator of the emergent behaviour likelihood – the more complex the system is, the greater the likelihood of emergent behaviours. Looking at differences between combat aircraft generations, it has been determined that the trend of increasing complexity is driven by a need for more value. It is also considered that increased complexity (irrespective of its value) is directly linked to increased cost, leading to a high risk of non-affordable complexity in the future. Managing complexity to create value is a key factor for the success of future development. In a complex aerospace industry with political intricacies and multi-layered organisations, everything is connected to everything. These interdependencies have been mapped in a "network interaction mapping" and the highest impact drivers have been selected as "key drivers". A methodology and its associated tool kit have been developed to evaluate complexity and value when comparing different options in a decision-making process. As the global geopolitical situation is volatile and uncertain, it is expected that Europe will face new forms of threats in the future. This will lead to future air platforms being systems of systems rather than standalone aircraft.

Key Words: Complexity, Fighter, Value, System of Systems, MBSE, Aerospace

Nomenclature

A/C	= Aircraft	*MBSE*	= Model Based System Engineering
COTS	= Commercial Off The Shelf	*MOTS*	= Military Off The Shelf
DAL	= Design Assurance Level	*MTP*	= Multinational Team Project
FAA	= Federal Aviation Administration	*RTOS*	= Real Time Operating System
LRU	= Line Replacement Unit	*S/W*	= Software

I. Introduction

The centrepiece of the ECATA Aerospace Business Integration 14 week training programme is the development of a technical and cross-disciplinary project called the Multinational Team Project (MTP). This is a project designed to facilitate the learning of collaborative skills through the exploration of a current and important aerospace topic, defined by the sector's leading academics and industry experts. The topic for the 2018 MTP was "Simple and Robust Aircraft: Challenging the Trend of Increasing Complexity".

Complexity within the aerospace industry has become an increasing issue during the last decades. This complexity has led to increased development costs, products with delayed entry into service and low maturity levels. Moreover, the complexity is linked to the likelihood of emergent behaviours that can jeopardise the planned value of a project. While the aviation industry is highly technological and capital-intensive, it has not been responsive enough to get innovative ideas at low complexity levels.

Looking at complexity source more closely, it comes from several different drivers and affects various areas simultaneously making it hard to understand. Therefore, each source of complexity will impact at different levels of the projects and organisations.

This report aims to provide a more comprehensive overview of the complexities and their sources and provides concrete strategies to tackle them. A potential scenario for the year 2030 has been proposed to show the applicability of these strategies.

II. Analysis of Complexity and its Consequences

Extensive research by the Federal Aviation Administration (FAA) based on existing papers, aerospace standards and guidebooks yielded the following definition retained for the further steps of the research (causes, impacts):

> *"Complexity is what results from large size, extensive coupling and behavioural emergence and negatively impacts the understanding of stakeholders, designers, and users" [Ref.2].*

Complexity is an indicator of the emergent behaviour likelihood – the more complex the system is, the greater the likelihood of emergent behaviours, which represents the relationship of the systems individual parts. Looking at the military programmes of the last decades and the differences between combat aircraft generations, the trend of increasing complexity is driven by a need for more value.

Indeed complexity, being a subjective concept, should not be viewed in isolation; it needs to be viewed in the light of company value creation as well. Examples of value created for the company could include:

Customer satisfaction

- Performance of the system
- Availability of the system (induced by reliability and maintenance efficiency, faster time-to-market)
- Usability of the system
- Reduced operating and ownership costs
- Market positioning
- Competitive advantage

Necessary complexity can be described as complexity that brings value to the company and so typically to the customer, too. Companies will need to manage this accepted complexity in the best way possible. In the evaluation of the accepted complexity, it is important to consider the negative impact it might bring to the creation of value.

On the other hand, the term unnecessary complexity can be used, when the disadvantage introduced by the complexity is greater than the value added for the company. This penalty can be evaluated in terms of cost, time or quality. It is also considered that increased complexity (irrespective of its value) is directly linked to increased cost, leading to a high risk of non-affordable complexity in the future.

Managing complexity in a way that it creates added value is the key factor for the success of future development programmes and a key enabler to avoid that Norman Augustine's 16th law "In the year 2054, the entire defence budget will purchase just one aircraft." [Ref.3] becomes reality. Thus, the drivers for complexity need to be clearly identified, their contribution to product value to be questioned and finally the right strategies to be defined in order to manage and/or reduce complexity.

III. Drivers of Complexity and Interdependencies

The first step to minimize and prevent this threatening trend will consist of identifying the drivers of complexity and their interdependencies. Through a series of more than fourty interviews with industry leaders, lecturers and extended research carried out during the ECATA Multinational Team Project, more than one hundred drivers and associated root causes for complexity in the former civil and military programmes have been identified.

The main root causes of complexity can be clustered into the following influence categories:

- Economic decisions
- Geo-political decisions
- Military aerospace industry standards
- Customers and company mind-sets
- High-technologic integrated products
- Necessary complexity

In a complex aerospace industry with political intricacies and multi-layered organisations, every action taken to "tune" one aspect of complexity will have repercussions on other complexities either directly or indirectly.

Over the project period, ECATA delegates attempted to map the interdependencies between all the 104 identified complexity drivers, and use an approach derived from genetic biology, "network interaction mapping". In this approach, the interactions between each element of the map ("nodes" – i.e. complexity drivers) are designated by a link ("edges" – i.e. logical links between complexity drivers). This concept can now be visualized:

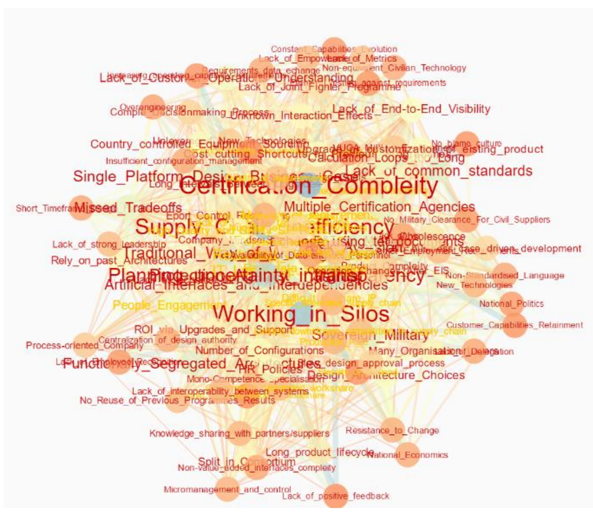

Fig. 1 Complexity Influence Model

This model allows us to understand hidden links and key influence drivers within a complicated network based on two key concepts:

- Degree Centrality – Amount of links to other nodes (first-degree)
- Betweenness Centrality (i.e. the relative power of a node within the network taking into account the importance of direct and downstream links)

Factually, 1042 undirected relationships were mapped between all 104 complexity drivers, node colour and text size were adjusted to reflect node Betweenness Centrality. The most important, influential nodes gravitate to the centre of the network, while less relevant nodes are drifting to the sides.

The ECATA 2018 group also created a web-page that allows end users to explore the complexity of complexity with their own devices (see http://www.ecata.org/MTP/#/). Finally, a concept of “Key Drivers” was developed, the notion of “Key” referring to the fact that they fall within reach of specific recommendations and actions that can be taken by organisations in order to manage them.

Through a five-why questioning technique, and a root cause analysis, of all the list of complexity drivers, it was determined where each complexity originated. The analysis was stopped as soon as a complexity driver could be addressed directly with relevant strategies. Using this approach, twenty-eight key drivers of complexity have been selected among the 104 as the highest impact drivers. These key drivers are then addressed with relevant strategies.

IV. Complexity Based Decision-Making Process

In addition to identifying the complexity drivers it is necessary to be aware of the complexity when making decisions, to ensure that the value increase justifies the added complexity. In a classical decision process, the company will assess the value (in a wide sense), the costs associated to the complexity of the solution and the risks linked to the chosen solution. However, adding an assessment of the complexity allows companies to derive the likelihood of emergent behaviours and even more the uncertainty of the anticipated value for the company.

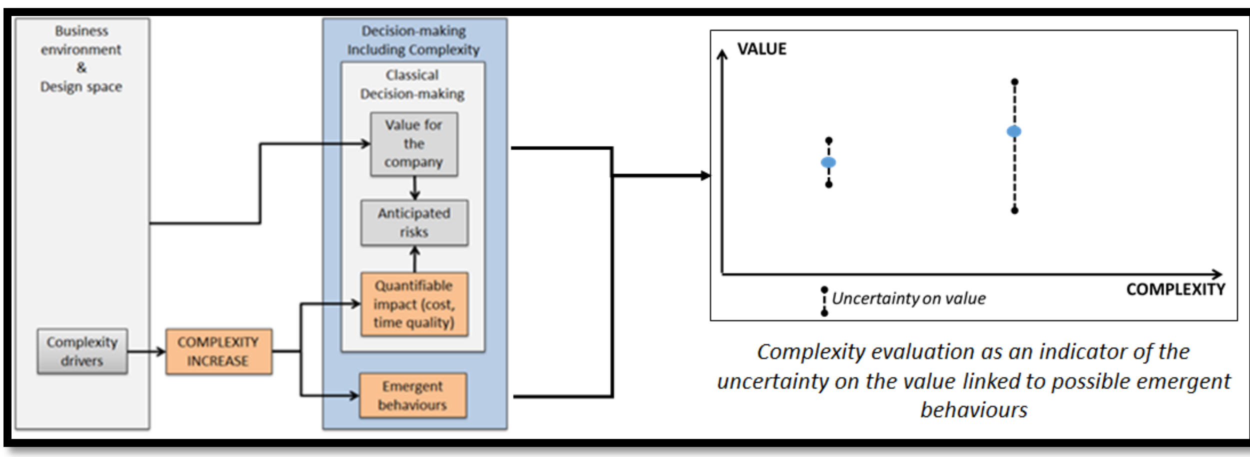

Fig. 2 Decision Making Process Considering the Complexity

A methodology and its associated tool kit have been set up to evaluate the complexity and the value of two options to help the decision-making process. Evaluation of the complexity is done by assessing metrics related to the key drivers of complexity. The computation of the final score relies on the impact of each metric all along the lifecycle of the product or service. Evaluation of the value is done considering the most relevant value drivers for the trade-off context.

The high customizability of this complexity evaluation tool makes it useable for any kind of trade off study. The selection of drivers and metrics available in the generic kit covers the main phases of the product lifecycle and enables an evaluation of the impact and benefits of strategies that could be developed to reduce or manage the complexity.

V. Strategies to Manage Complexity

When the complexity in the solution has been evaluated, this can prioritize the area to investigate for strategies to reduce or manage that complexity. The following seven strategies have been developed providing the greatest coverage of the identified sources of complexity:

- *Ensuring More Efficient Workshare* – to smart split of responsibilities among stakeholders based on capabilities and create efficient structures while promoting performance and win-win partnerships.
- *Taking Modular Approach through a Functional Driven Architecture* – to remove close coupling of software and hardware that will make solutions resilient to change and obsolescence, while increasing opportunities for future reuse of software or equipment.
- *Being Inspired by Other Industries* – to take benefit of the proven products, relevant practices and experienced people from adjacent businesses, especially civil aeronautics.
- *Defining Requirements Collaboratively* – to mitigate the complexity as early as the needs/requirements collection phase through dedicated workshops led by the prime contractor(s) and involving the different stakeholders.
- *Using MBSE to Manage the Complexity* - to replace the document-based approach by a model exchange, fostering the concurrent engineering during the whole design process.
- *Harnessing Full Potential of Data* – to describe the organisational and mind-set enablers the aerospace industry must implement to unlock the value in its existing data and reduce complexity across its entire lifecycle.
- *Staying Agile and Vision Driven* – to engage your team and your company to better performances.

All the complexity drivers can be clustered into six influence categories which can then be further linked to the strategies developed (see Fig. 3). By identifying the links between strategies and the drivers they address, along with the category of each corresponding driver, it is possible to demonstrate that the seven strategies provide significant coverage of the identified sources of complexity.
As a function of the area of influence and the likelihood to be able to influence the key drivers within a given strategy, complexity can now be considered to be: (1) Accepted and managed (if bringing value); (2) Reduced (if possible); (3) Challenged or removed (if intolerable)

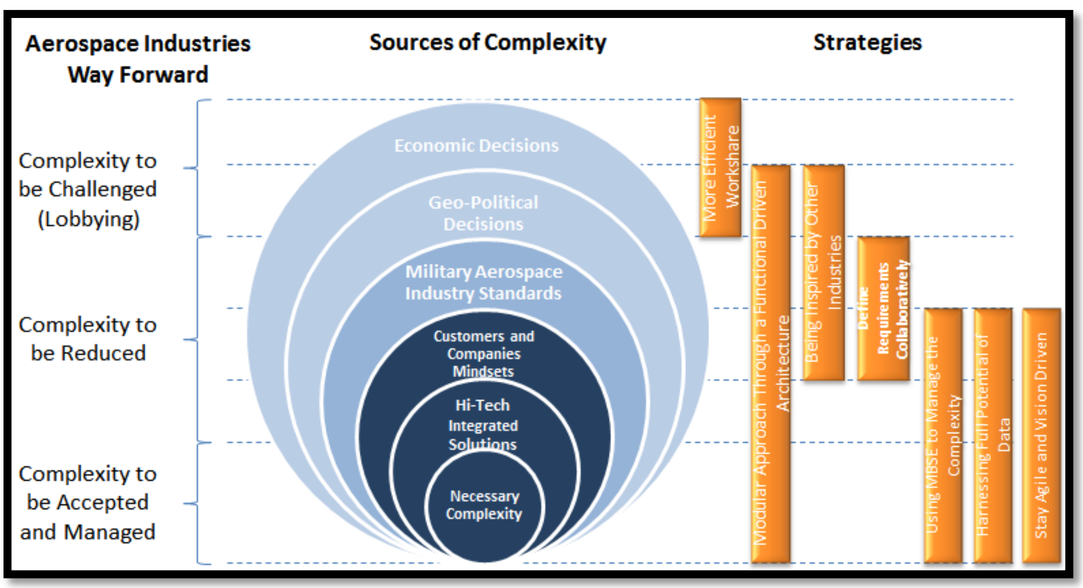

Fig. 3 Categorising Approaches to Complexity

VI. Europe 2030 Scenario

The global geopolitical situation is volatile and uncertain, and Europe may face many kinds of potential threats in the 2030+ timeframe. Previously, European defence capabilities have been used primarily for crisis management and deployment but territorial defence is becoming increasingly important. Future adversaries are expected from both ends of the technology spectrum – advanced capabilities such as hypersonic missiles and rail guns, while also facing readily available asymmetric threats from domestic terrorists and cyber warfare. This range of threats will lead to future air platforms being systems of systems rather than standalone aircraft and related mission profiles will require advanced capabilities to be implemented:

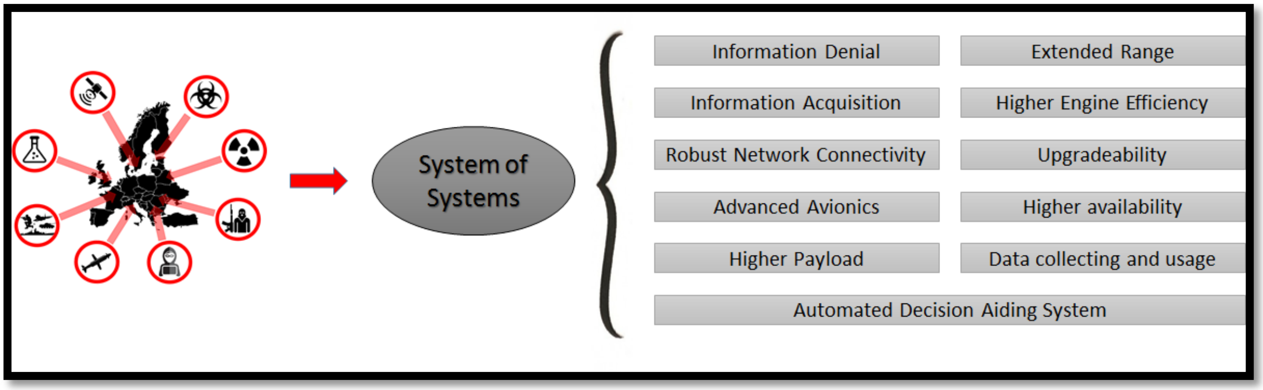

Fig. 4 Future Threats in Europe Vs Top Level Requirements for aerial combat platforms

In a system of systems scenario, technology improvements are required to help the pilot to focus on his job of coordinating.

Reliable and encrypted communication systems with sufficient bandwidth are needed to share the great amount of mission data between the platforms. The fighter aircraft must be able to process the data and signals in real-time and support the pilot in the decision making. Since more and more data is collected, improved data downloading as well as tools and ability to use all the data will be needed.

A higher operational maturity at delivery is necessary from the air forces perspective. Since the future battlespace and threat environment is uncertain and technology development is accelerating, future fighter aircraft need to have a flexible design enabling shorter and more frequent update-cycles to address in-service issues and be able to introduce additional capabilities faster.

Operators and ground crew require an aircraft design optimised for daily operation of the aircraft. This is essential for the effectiveness of air forces, as fleet sizes are reduced compared to the situation decades ago. To provide enough flight hours and guarantee sufficient pilot training, a higher availability than actual legacy fighter aircraft is required. The following aspects need to be considered for the development of a next generation aircraft when optimising for daily operations:

- More robust design to reduce general need for maintenance
- Elimination of unnecessary complexities
- Short turnaround time
- Optimised fault identification including procedures (majority of faults identified in aircraft, otherwise with LRU (Line Replaceable Unit) test equipment outside aircraft, as last step sent to supplier)

The ability to perform different mission profiles simultaneously with a single aircraft configuration (omni-role capability) in combination with the above listed capabilities is considered being the key element for the next generation aerial combat systems. These advanced capabilities will lead to technology-driven complexity that cannot be avoided. The complexity must be better managed to avoid further increase in cost and break the continuing trend of reduced value for the customer.

VII. Applying Strategies to a Mission System

Since the Mission System is a system of systems designed to fight complexity for situational awareness, it is a useful example to illustrate how to apply the strategies and the benefits that can be achieved.

By working collaboratively from the start of the programme, both the customer and the industry can have a common understanding of the operational environment and the needs. This will benefit the programme by reducing the probability of complexities associated with misunderstanding and changes late in the programme. It presents an opportunity to challenge customer requirements and also reduce over-engineering.

During the initial design phase, adopting a functionally modular architecture supported by a Model Based Systems Engineering approach can ensure there is a single source of truth for the design and subsystems have a clear and unambiguous scope. Functional decomposition will also enable a more efficient workshare allowing the subsystems to be delegated to the suppliers with the most suitable technical capability and experience. By clearly defining functional modules, suitable modules may be available from other industries, i.e. from commercial logistic software.

Due to the high technological nature of the system, a high degree of complexity will remain. However, by using the strategies described above the uncertainty associated with the complexity will be reduced and the emergent behaviour will be more manageable.

The following infographic describes how to apply, practically, the strategies in the context of a future Mission System development. The various stages are described in more detail within the following paragraphs. Also, where it is suggested that a strategy is applied a number has been associated with the stage.

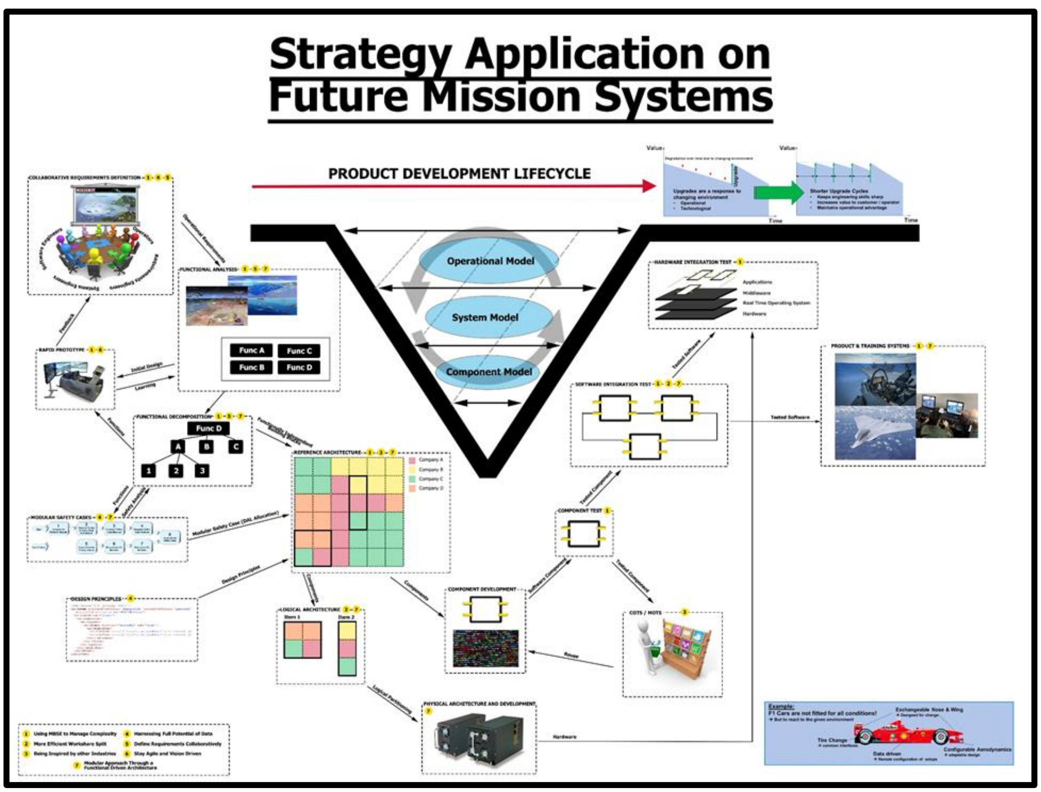

Fig. 5 Strategy Application on Future Mission Systems

A. Collaborative Requirements Definition

At the start of a future fighter development programme, it is essential that the industry and the customer have a joint understanding of the military needs and work through a 'One Team' approach. This can be achieved by conducting collaborative requirements workshops in order to determine the operating environment and set the landscape for product development. The workshops described should, as a minimum, be attended by operators, customer representatives, systems engineers, software engineers and requirements engineers. It is recommended that workshops make use of MBSE techniques which shall be stored in an operational model, to capture the output and to ensure consistency with the following steps.

B. Functional Analysis

The aim of this activity should be to determine top level functions, inside the boundary of the system of interest, which would be needed to meet the goals required by the end user. The analysis should also identify interface exchange requirements that describe how the system will interact with other nodes. The functional analysis could be undertaken in conjunction with the same stakeholders described in the previous step. Functions in each scenario should be defined in a way that they are generic so that they become modular and can be re-used in further analysis.

C. Functional Decomposition

Following initial functional analysis, it would be possible to decompose the functions into lower level functions. By identifying patterns in the design (i.e. similar functions and sub-functions appearing in analysis) it is expected that elements of the system model can be re-used. This is likely to reduce the time required to develop the functional architecture and also make it modular.

D. Rapid Prototype

To verify if the requirements and design will satisfy the need of the customer and end users, system prototypes of the mission system should be built. Initially, these rapid prototypes would be very immature, but would allow operators to validate that requirements have been captured correctly and to influence design decisions later in the lifecycle. The prototype will evolve to reflect the functional system design and will provide chances to rapidly iterate the design taking influence from operators. It may be possible to take advantage of MBSE techniques to produce rapid prototypes from the system model.

The rapid prototyping approach in complex environment is an application of the fail fast, fail cheap principle from the agile working methods and therefore benefits from the mind-set to be built. As a by-product of having a system prototype available early in the lifecycle, this would also allow the military community to develop their initial operational procedures earlier.

E. Modular Safety Cases

Undertaking safety analysis early in the lifecycle is key to ensure that the resultant architecture (reference, logical and physical) has the correct layout to ensure successful certification. To ensure that the architecture is resilient to change, it is necessary that safety arguments are constructed such that changes to modules do not impact the overall safety case, thus minimising the amount of retesting and recertification.

Using a modular safety analysis enables the reuse of safety cases in the future thus reducing the cost. Issues with reusing safety information from systems owned or operated by other entities can be managed using the Big Data architecture suitable for time series processing and blockchain encryption technologies.

F. Reference Architecture

The Mission System reference architecture will represent the modular functions and their associated service elements that make up the system of interest. In addition, the reference architecture may describe functional constraints (such as Design Assurance Levels (DALs)) that will support the generation of low level software requirements.

The reference architecture does not describe the specific instantiation of a system, but it acts as a reference framework standard that software components should comply with. The reference architecture will be the output of the analysis undertaken using MBSE principles. The following picture gets an overview about how MBSE can be widely used in the Mission System development.

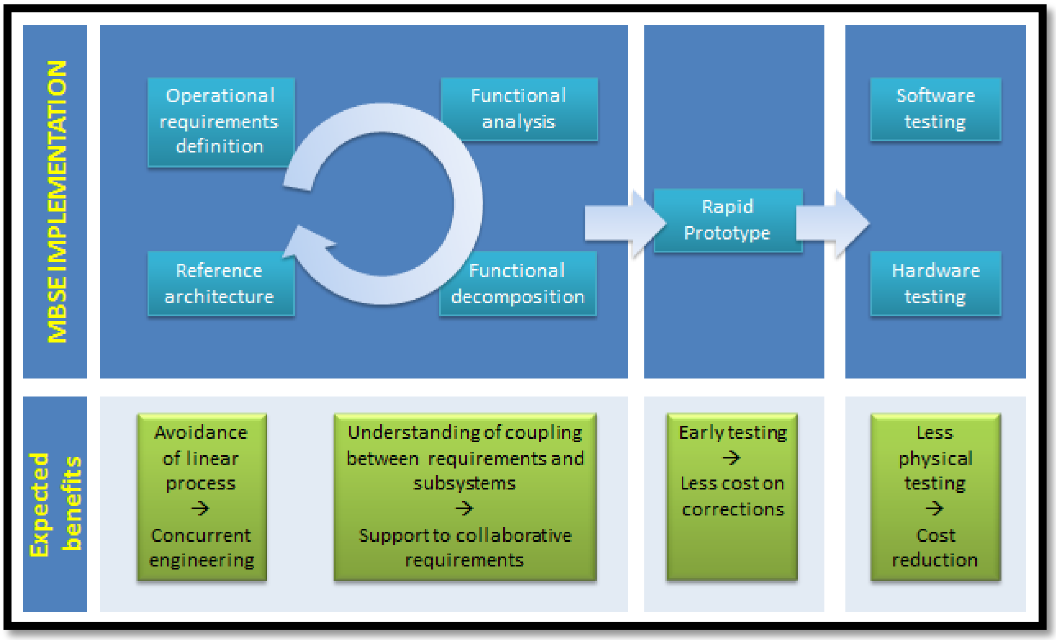

Fig. 6 MBSE Approach on Mission System Development

When the reference architecture has been created, it would be also possible to use this reference to allocate an effective workshare between organisations. This could be undertaken through the allocation of software component development to suppliers such that it is developed to the correct integrity levels, interfaces and functional definition. Suppliers should contribute to the technical solution and with technology, selections should be made on companies' technological know-how and experience.

G. Design Principles

To ensure that software can be easily configured (and re-configured) through the life of a product, design principles should be adopted. A data driven approach would be an example design principle. This approach attempts to determine core functionality required in software and the variable elements which could be turned into data and used to configure the software.

H. Logical Architecture

Following the determination of a functional reference architecture, a logical architecture should be developed, which would indicate how functional components and their associated services should be interconnected on a specific implementation. This architecture would also be required to show how the design would allow satisfaction of the safety and data security arguments.

The logical architecture would present a further opportunity to allocate workshare in an effective way. It is recommended that the prime contractor focusses on the architecture level (i.e. elements up to this point) and suppliers on the technical solution/technology.

I. Physical Architecture and Component Development

The physical architecture would describe how the software, middleware, real-time operating system and hardware shall be configured on the aircraft. When defining the middleware, Real Time Operating System (RTOS) and hardware, care should be taken to ensure that the design choices support the flexibility, abstraction and upgradability requirements. Size, weight and power constraints would likely have been applied to the mission system at this point through a top down budget allocation.

Software components should be developed in line with the reference architecture identified. These components should be complete with the functional and service definitions described therein.

J. COTS/MOTS

As software components have been designed for reuse, the developed and tested software can be made available (along with the test evidence) to other projects and programmes that may require the same functionality. If other products adopt the same reference architecture, then the software component can be directly reused, and software would become Military off the Shelf (MOTS).

Conversely, commercially developed software, or, Commercial off the Shelf (COTS) software is available that fully/partially meets the functional requirements, considerations should be made as to whether it should be used in the development. As described in the civil re-use strategy care should be taken as to the constraints of the civil components (e.g. export constraints, integrity level).

K. Component Test

Software component test is the lowest level of testing. Before system testing can be done, the components of the system should be tested to find errors and correct them as early as possible. The component test should focus on functional testing of the components. Taking advantage of MBSE principles it would be possible to streamline the test process.

L. Software Integration Test

Software integration testing is testing of two or more components together and can be performed on different levels (e.g. testing only two components or testing a complete system). By using the models developed earlier in the development cycle, using MBSE, new or updated software components can be tested early in synthetic environments. The synthetic environment may contain only models of the interfacing systems, models of the complete mission system and/or models of the aircraft together with a tactical and visual environment.

By sharing models with strategic partners and suppliers more accurate and earlier software integration testing can be performed. It is important to define test cases (and store resultant evidence) in a way that does not compromise the benefits of a modular approach.

M. Hardware Integration Test

Hardware integration test is the testing of hardware components together with other hardware or software components. As soon as hardware is available instead of the models used in the synthetic environment, it can be tested in a semi-synthetic. By reusing system models and allowing the models to be easily replaced by hardware the test rigs will be flexible and upgradable for future development efforts.

N. Product and Training Systems

By taking a functional and modular approach to develop mission systems software, the abstraction from a hardware instantiation during design would allow the software developed on the target aircraft system to be reused in training devices/simulators. This approach offers great benefits in that the training devices will be fully representative of the actual Mission System. Also, through MBSE methods it would be possible to reuse representations of hardware (i.e. sensors) such that the end to end simulation is closely aligned to the aircraft systems.

In conclusion, applying some of the strategies above described to a future Mission System development programme we can get the following benefits:

- Optimised Number of Physical Computing Elements – Following a modular approach, by considering software design at an abstract level, allocation of software to hardware can be performed with a whole system view. This would optimise the number of physical computing elements within an aircraft thus reducing the overall size, weight and power budget requirements.
- Development Cost Reduction – Several strategies have been applied with the aim of reducing development costs:
    - Early testing by means of MBSE approach: The later the tests are performed the higher the likelihood of incurring on extra costs.
    - Testing by simulation: Using the models created in the first phases for MBSE convergence of requirements and architecture. Thus, no additional investment needed, and savings are done vs the physical testing.
    - Due to the lower number of physical components, derived from the modular approach chosen, some cost synergies are found. Similar savings are expected when (modified) civil approaches or equipment may be used.
    - Less variability of the requirements: It can be achieved by means of the Define Requirements Collaboratively strategy (using SysML as a common exchange language) and use of MBSE in the convergence between requirements and architecture, together with the operational data used for requirements challenge; the requirements should be more robust than in a conventional approach, avoiding the costly requirements update in the last phases of the design
    - By proposing MOTS/COTS, the cost of validation and certification of new components can be dramatically reduced.
    - Creating an architecture based on the functionalities, allows to define efficiently the workshare. All the common functions can be assigned to a specialised supplier. This way of working will make the testing phase more efficient too.
- Configurability – By taking data driven approaches it would be possible to rapidly change the configuration of a Mission System resulting in the system being capable of being more reactive to changes in the operational environment.
- Upgradable – due to the construction of the design and the supporting test evidence following a modular approach, the cost and time required to change Mission System components should be minimised. This may increase the amount and frequency of change cycles which a military aircraft would undergo in its life.
- Re-Usable – as a reference framework and modular software components (with supporting test evidence) would exist using the described process it would be possible to make the output available for secondary usage. The secondary usages may encompass, training devices, simulators and similar aircraft development projects.

- Improved Availability – Through the recovering of the operational data of the system, a programme of predictive maintenance can be set. Instead of doing maintenance of the hardware based on fixed cycles, it can be customised and planned based on the actual operational use.
- Improved Operability – By considering in a collaborative way the requirements, and so, the pilot requirements too, and using MBSE to convert these requirements into functional and logical architecture, we ensure that the system is compliant with the final user requirements.

However, some considerations have to be taken when applying this development strategy:

- More upfront investment needed, to set up the MBSE approach with common languages and infrastructure of models' communication. The recommendation is that MBSE should not be used once the function decomposition is done among the different suppliers.
- More upfront workload, with longer convergence periods on the requirements definition, functional decomposition and early testing, due to the collaborative requirements and modular approach. However, the benefits on the next phases of the development do compensate these early phases effort.

VIII. Conclusion

Complexity within the aviation industry has become an increasing issue during the last decades, leading to increased development costs, products with delayed entry into service and low maturity levels. Moreover, complexity increases the likelihood of emergent behaviours, inducing an uncertainty around the anticipated value for the company. However, this complexity is necessary and cannot be avoided especially in the military context for 2030. There will be no simple aircraft but there are still means to better manage the needed complexity.

Assessing the complexity in the decision-making process allows to ensure that the complexity added is justified with the value increase, to better anticipate and accept these consequences, and maybe to avoid future issues. Strategies are also available to properly manage the complexity by addressing its key drivers.

The global geopolitical situation is volatile and uncertain and the Europe faces many different kinds of potential threats in the 2030+ timeframe. This range of threats will lead to future air platforms being systems of systems rather than standalone aircraft and related mission profiles will require advanced capabilities to be implemented. As an illustration of the identified solutions, the development of the mission system for a 2030 military platform can benefit from identified strategies to manage complexity all along its lifecycle. Game changing disruptive ideas for future systems can also encourage a step change in the industry, considering the advantages they would provide.

Acknowledgments

The ECATA team 2018 would like to thank all of the individuals who have supported us along our journey.

First of all we would like to thank our companies, for the opportunity and the investment in our development.

A big thank you also goes to:

Our customers for the MTP: Víctor LAFUENTE-GARCIA from Airbus, Mark DIMECK from BAE Systems, Stéphane DURAND-GASSELIN from Dassault Aviation, Markus HOLZER, Dr. Daniel NAGY and Tobias LAMBRECHT from Liebherr, Kirsten AHL and Tobias JANSSON from Saab Aeronautics, Delphine DIJOUD from Safran.

The *ECATA Management Board* for all the organization prior to and during our training.

The ECATA coordinators: Thibault BREMAUD, Claire JUANEDA and Michel BOUSQUET (ISAE-SUPAERO Toulouse), Dr. Marcos CHIMENO and Hugo ALIAGA (Universidad Politécnica de Madrid (UPM)), Dr. Albert

PERNPEINTNER and Amely SCHWOERER (Technical University of Munich (TUM)), Dr. Mark VOSKUIJL and Kimberley GRAAUW (Technische Universiteit (TU) Delft) for their continuous support during our training.

Our advisors for their tremendous contributions to our work: Olivier COUDRAY, Franck FLOUERNS, Jean Guy GOUTAUDIER, Pierre HAUTY and Henry MOET from Airbus, Simon BARNES, Mike BIELBY, Stuart BUTLER and Nick COLOSIMO from BAE Systems, Yannick HAUX from Dassault Aviation, Bertrand LAPOUTRE from French Ministry of Defense, Paolo CHIMETTO, Antonio DE ROSA, Nunzio DI PEDE and Elio PESCI from Leonardo, Jan UHLIG from Liebherr, Blanca PES MORENO from MTU, Laurent BAUDEL and Pascal GAUDIN from One Web, Torvald MÅRTENSSON, Annika MEIJER, Jörgen MEIJER, Sven ÖBERG, Knut ÖVREBÖ, Nils-Erik PETERSON, Marcus WANDT and Anders PETTERSSON from Saab, Michel EYMARD, Nicolas GUEIT, Thomas PICOT and Michel ROTTA from Safran, Piero LANDOLFI from Tesla, Rana ALKHADI, Jan Ole JOHANSSEN and Bernd BRUEGGE from Technische Universität München, Clément NOUVEL from Valéo.

All of the lecturers involved in the ECATA ABI 2018 course.

And finally to our families for all of their support and patience during these months.

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