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REPORT FROM ICAS WORKSHOP ON COMPLEX SYSTEMS INTEGRATION IN AERONAUTICS

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Abstract

This is a report on the 2015 ICAS Workshop on Complex Systems Integration in Aeronautics. The workshop included the participation of industry leaders from around the world. This summary consists of three main sections addressing the outcome of the workshop in the context of common themes, unique insights, and new directions and recommendations.

1 General Introduction

The ICAS Programme Committee (PC), comprising over 50 representatives from the world-wide aeronautics communities, met at Krakow, Poland to plan for the 2016 Congress. ICAS took full advantage of this gathering by hosting a one-day workshop on 31st August 2015, on the subject of *Complex Systems Integration in Aeronautics*.

As airplanes become more and more integrated systems, their subsystems, components, and interfaces also become more complex. The operating environment for these airplanes is also increasingly congested and complex. The scientific approach needed to design, develop, and operate this very complex system, i.e., “systems integration”, seriously challenges traditional systems engineering methods. Our PC in Krakow focused on this issue, thus firmly establishing the importance of the ICAS workshop.

At the workshop, invited speakers gave presentations on a wide range of topics, from the latest research and development achievements, to implementation and operational experiences in systems integration issues. The speakers covered both defense and commercial platforms, with particular emphasis on dealing with system complexity challenges from a complete aircraft lifecycle perspective. Their presentations stimulated significant discussion and multiple new directions were recommended. The outcomes of the workshop include these new directions and are presented in this report to inform the 2016 ICAS Congress. The objective is to improve our overall level of understanding of this issue, and to assist in setting directions that will benefit our global industry, and the customers and stakeholders that it serves.

The following is the list of presentations and their authors:

i. Innovation in Aircraft Complex Systems Integration
Sebastien Remy, Head of Innovation Works, Airbus Group, France

ii. Complex Systems Integration from Defence Science & Technology Perspective
Dr. Ken Anderson, Chief of Aerospace Division, Defence Science and Technology Group, Australia

iii. Co-Evolution of Aeronautical Complex Systems & Complex Systems Engineering
Dr Xinguo Zhang, Executive Vice President, Aviation Industry Corporation of China, China

iv. Technological Challenges and Opportunities in Systems Integration

Pierre Fossier, Vice President, Chief Technical Officer of the Air Operations Division, Thales Group, France

v. Systems Engineering in Complex Systems Integration
Stefan Roemelt, Vice President, HO Avionics Platforms & Electrical Systems Systems Engineering – EYN, Airbus Group, France

vi. Aircraft Systems Integration from Embraer Perspective
Joao Paulo Reginato, Systems Integration Manager Chief Engineer Office, Embraer, Brazil

vii. Overview of the MRJ Programme and Systems
Junichi Miyakawa, Senior Chief Engineer, Mitsubishi Heavy Industries Ltd (MHI), Japan

viii. Systems Integration for Capability, Flexibility and Affordability – Gripen Avionics Upgrade
Gunnar Holmberg, Director New Business, Saab Aeronautics, Sweden
Billy Fredriksson, Chief Technical Officer (ret.), Saab AB, Sweden
Anders Pettersson, Senior Manager Product Engineering /Chief Architect, Saab Aeronautics, Sweden

This report is organized into three sections for synthesis of the above eight presentations:

- Common themes (section 2)
- Unique insights (section 3)
- New directions and recommendations (section 4)

2 Common Themes

2.1 Architecture

One theme that can be seen in all of the presentations commencing with Remy [1] is that managing systems complexity requires an abstraction that allows the designer to leverage layers of system attributes. This layering addresses the complex design requirements and allows development of the "architecture" (abstract description of each layer and its entities, and the relationship between the entities) as the foundation for the design requirements. This differs from the traditional approach in which for example, system requirements from the onset were decomposed in physical terms to various ATA (Air Transportation Association) -chapter-systems in order to design each subsystem. This traditional approach (abstraction to ATA chapters as system architecture) for today's more complex and integrated systems) could result in emergence of problems such as sub-optimization or nonlinearities.

Anderson [2] concluded that there has been an increasing focus on integration in defense acquisition, in operations and in sustainment. One key element of the joint integration is "architectures". In addressing Model-Based Engineering as a method to leverage modeling capabilities, Zhang [3] stressed that abstraction and encapsulation are key principles for managing the complexity of systems. He concluded that a disciplined approach (with structured process knowledge) is needed to deal with the inherent uncertainty in complex systems. In this disciplined approach, the requirement system architecture is critical. Fossier [4] discussed architectures from three perspectives (summarized below in Unique Insights). He concluded that in the upstream Model-Based Systems Engineering (MBSE) process, Concept Development and Experimentation (CD&E) and "Architecting" is key to engineering.

In the example of the electrical systems integration of the Airbus A350XWB, the first topic Roemelt [5] addressed was system "architecture" and the architecture design drivers. Similarly in the Embraer presentation Reginato [6] discussed the evolution of avionics architecture from one that was federated (in a "lowly integrated aircraft and low complexity") to a highly integrated aircraft where the networked Integrated Modular Avionics (IMA) architecture included some key non-avionics functions. In parallel to the evolution of these architectures is the development of increasingly more disciplined validation and verification approaches ensuring the safety of highly complex integrated systems. In particular, in contrast to traditional physical integration and tests, a large amount of work is needed in the functional analysis and virtual integration to ensure that the physical architecture will lead to physical systems that meet requirements. This was discussed in presentations [5]-[8], and Holmberg et al. [8] eloquently concluded that "architectures and integration are key for capability, flexibility, and affordability throughout the life cycle".

2.2 MBSE

Model-Based Systems Engineering (MBSE) is defined as "the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (INCOSE [9]). Zhang [3] gave the description of the MBSE through complex systems engineering evolution, which included four major steps (see Fig. 1: Evolution of Complex Systems Engineering):

1.0 Traditional systems engineering approach was used while most of the system (technology) was a "mechanical" system.
2.0 Computer-aided tools were used and the driving technology of the systems was a "mechatronic" system.
3.0 Structured process was used, such as modern management methods. The technologies become more integrated with increasing importance of the computer (information) technology including impacts in the embedded system.
4.0 Knowledge based approach via modelling ("modelling knowledge") needs to be used for a highly complex "cyber-physical system".

It is noted that between stages 3.0 and 4.0, there is a key paradigm shift to the approach. Instead of relying on lots of documents in systems development (e.g. requirements in "document-centric" approach using "natural language"), models are the main output / artifact of Systems Engineering as "knowledge" and provide a means of communication throughout the product life cycle. So MBSE has become the critical method for the fourth step mentioned, and for cyber-physical systems development. This conclusion was echoed by other workshop presenters.

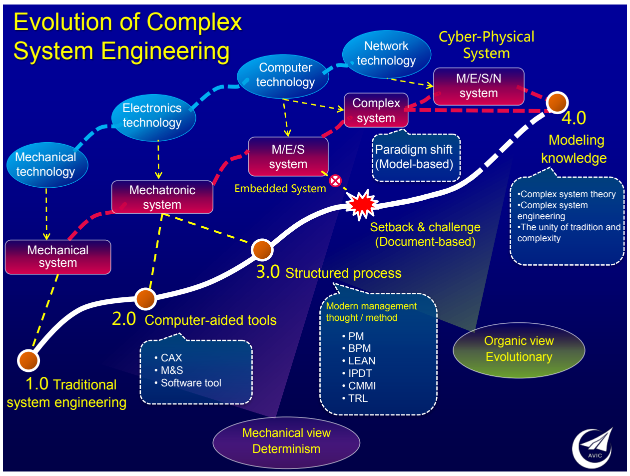

Fig. 1. Evolution of Complex Systems Engineering (from Zhang [3])

Fossier [4] described the transformation from "requirement modelling" to "architecture modelling". The model-based architecture hierarchy included: the operational analysis (activities) model; the system functional model; the logical architecture model; and then the physical architecture model. It was also explained in this presentation that the upstream MBSE allows concept development, experimentation and "architecting", and the downstream MBSE allows early validation.

Both Zhang [3] and Reginato[6] stressed the importance of "continuous verification". This increased effort of MBSE on the "left side" of the V (Systems Engineering process), through multiple analyses, gives an understanding of the various systems behavior "before" decomposition to the next level of requirements, thereby reaching a truly optimized systems architecture.

The benefits of MBSE are summarized by Holmberg et al. [8]:

- Early Knowledge and storage of knowledge throughout life cycle,

- Shared understanding of requirements and solutions;
- Improved competitive lead times and quality;
- Increased confidence and reduced testing.

The next steps and the challenges for MBSE were best summarized by Fossier [4]:

- Federating models or simulations
- Eliciting, expressing, and comparing candidate solutions;
- Multi-criteria decision making.

3 Unique Insights

3.1 Novel Configurations in Aircraft Design

For aircraft that are dramatically different from conventional aircraft (in terms of systems configuration such as energy source), the traditional optimization has limits as Remy [1] illustrated. For example, new options such as full-electric or hybrid-electric propulsion systems demand new requirements in energy storage and distribution, and in systems integration that present unprecedented challenges. These call for novel configurations (e.g. distributed propulsion, aircraft sizing) and lots of scalability and modeling studies to better understand the system-level behavior in order to achieve an optimum design. Aside from the certification and operational transformations that must be made for these novel configurations, according to Mr. Remy, the "intuitive knowledge" (e.g. the knowledge gained from conventional aircraft design) does not yield any value for the new configurations. An implication here is that younger generation aerospace engineers will need to think and act in a "different framework". Perhaps this calls for a new curriculum (or discipline?) in acquiring the knowledge necessary for future aircraft systems integration.

3.2 Complexity

Using a two-dimensional perspective, Fossier [4] described "complexity" covering three areas (see Fig. 2). The first area (bottom left corner) is characterized by lower levels of interaction and smaller to medium system scale and is titled "technology driven system architecture". The system complexity in this area mainly relies on hardware, technologies and algorithm. The systems from the past decade (2000-2010) were primarily in this category, i.e., technology driven. In the current decade (2010-2020), systems characteristics are function driven, as shown in the middle (diagonal) band. In this "functions driven system architecture", MBSE is used extensively. The complexity mainly relies on a high level of interaction between functions, non-functional constraints, interfaces, and data components. For the future (2020-2030), "capability driven system architecture" is the third area and is characterized by the higher interaction and higher system scale shown in the upper right corner. The complexity comes from complex interactions between operational needs, capability and services, business processes and organizations.

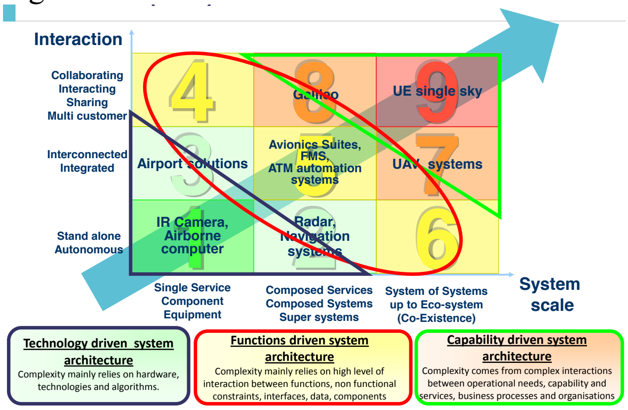

Fig. 2. What Is Complexity? (from Fossier [4])

3.3 Future Challenges

In the defense science and technology arena, Anderson [2] summarized the integration challenges as follows:

- Increasingly complex individual capabilities
- Impact of "off the shelf" acquisition – many shelves
    - Many different suppliers over 10+ years
    - No common approach to

integration or standards
- Acquisition process not optimized for integration
    - Large number of disconnected projects/ programs
    - Poor or late integration across projects
- Inadequate overarching design / architecture
    - Unclear concept for usage and operations
    - Not integrated by design
    - Not designed for change
- Often overlooks the "human dimension"
- Processes are not well suited to manage enduring and evolving capabilities

From tomorrow's "capability driven" system architecture perspective, two challenges for complex systems integration were identified by Fossier [4]:

i. System definition unstableness:
    a. This may arise from unstable problem space, unstable solution space, or unstable stakeholder space, including the systems in "system-of-systems context".
    b. Obsolete deliveries due to very long cycles on the technical as well as on the functional and operational side.
ii. System testing incompleteness and operation unstableness:
    a. In these complex systems, full testing is becoming non-achievable.
    b. Some testing is not achievable in the real world at a reasonable cost or schedule.
    c. Lessons learnt from system operations will bring need to be satisfied in short loops.

Another unique insight regarding integration challenges shared by Reginato [6] is in the safety and security area (for the latest avionics systems development). There are rigorous standards (e.g. for processes) in the development and assessment of systems at the systems, subsystems, and items level. However, as the airplane and the systems it operates in (e.g. manufacturers, airlines, air traffic management, maintenance operators, etc) become more and more network-centric, system security becomes more vulnerable and presents increasingly serious challenges. That is, the security issues may be manifested in broader safety and security problems. Consequently, more rigorous standards and/or processes would be needed for the potential cyber security requirements.

3.4 Affordability

While complex and sophisticated jet fighters like the Lockheed Martin F-35 Joint Strike Fighter, Dassault Rafale and Eurofighter Typhoon dominate the headlines when it comes to the global fighter market, not every country needs or even wants a top-of-the-line warplane. Some nations may opt for Russian or Chinese-built machines. In particular, there is a sizeable market for "lower cost alternatives". It is this market that the Saab JAS-39 Gripen dominates. Holmberg et al. [8] showed that while performance growth due to mechanical and material technologies has doubled approximately every 20 years, the performance (functions) deriving from the new systems and information technologies has grown exponentially. These technologies include computers and electronics, sensors technology, data fusion, command and control, autonomy, micro mechatronics etc. Even though, for most airplanes, the cost for developing and integrating, operating and maintaining systems with these higher performance requirements will also increase, "Gripen has 'broken the cost curve'" (see Fig. 3), i.e., its life-cycle cost is reduced while still delivering the operational effect. The Gripen demo indicated "higher than 50% increased development efficiency". The key in realizing this efficiency and reversal of cost growth is summarized as follows (Holmberg et al. [8]):

- Innovative environment
- Efficient architectural design and systems integration (also mentioned in section 2.1)
- Management of supply chain
- New methods, tools, and processes (e.g. MBSE, also mentioned in section 2.2)

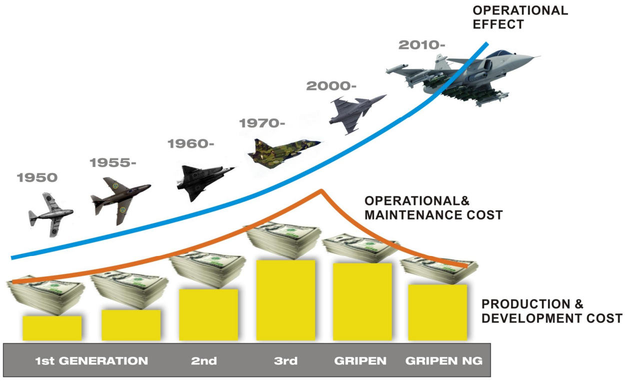

Fig. 3. GRIPEN – Breaking the Cost Curve (from Holmberg et al. [8])

4 New Directions and Recommendations

This summary report presents common themes and unique insights synthesized from eight presentations delivered at the 2015 ICAS Workshop on Complex Systems Integration in Aeronautics. These presentations identified cutting-edge development challenges and requirements for integrating complex aerospace systems. In the past, the approach was to ‘divide and (then) conquer’ to develop large-scale systems. However, the new directions that arise as a result of modern large complex aeronautical systems necessitate a paradigm shift. It will be critical to take the holistic view and focus a great deal of effort at the front end of system development. This approach can be represented as ‘conquer and then divide’. New methods, such as continuous verification and the use of modeling and simulation such as MBSE, enable the effective implementation of such an approach.

To utilize these new approaches for complex systems integration, the aerospace industry needs to make some process changes including adaptation (and development) of new tools and methods. The industry also needs an infusion of “integration skills”, particularly skills with multi-disciplinary background and experience with new modeling and simulation methods. At present, few academic institutions offer comprehensive training in these skills, and available programs are particularly limited in the area of applications. An important recommendation is for universities with aeronautics curricula to offer this type of training to prepare students for future industry demands. This could be achieved as senior level capstone projects or as graduate research programs.

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