# Next-Generation Model-Based Systems Engineering Processes and Tools Supporting the Airworthiness efforts of Cyber Physical Systems (CPS)


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## ABSTRACT


Efficient and cost effective deployment of software intensive cyber physical systems (CPS) in military aircraft remains one of most complex and challenging issues facing Government Program Managers. Current tools and methodologies are not adequate for the development and certification of CPS as they create affordability and schedule dilemmas for current and future programs. This is due to poor requirement definition and the inability to identify and document hazards created by complex hardware/software interactions. New technologies, particularly advances in model-based engineering and tooling show great promise for correcting these challenges and improving the safety and airworthiness approvals for CPS. Unfortunately, Model Based System Engineering (MBSE) processes and tools are challenging the bounds of current Government business and acquisition practices creating a dilemma for the development and fielding of future Military Aircraft.

Government airworthiness processes further complicate the adoption of novel engineering approaches in support of fielding capabilities. Existing certification approaches rely on a bevy of artifacts, primarily paper documents, to provide visibility into the system engineering and process maturity of an aircraft development as a proxy for direct evidence of the safety and flight worthiness of a system. The reliance on documents alone provides no clear insight to system function and operation for airworthiness authorities, and these large and costly documents are deemed by many Program Managers to provide little value. Additionally, these artifacts are prone to error due to the limitations of static documents, which are often out of sync with the technical implementation of the underlying system. The use of a robust MBSE approach to software intensive systems is a suggested improvement to provide true airworthiness cognizance in the form of dynamic and configuration controlled models capable of showing system, subsystem and component function rather than a reliance on static artifacts to support certification efforts.

The Government and Industry Program Managers need improved end-to-end model-based (MB) tools to assist with the management of these complex development efforts, while airworthiness authorities need clarity of how MB tools and processes are available to support their airworthiness efforts.

This paper presents a vision with options for embracing MBSE practices; it suggests how the Government could use MB tooling and process improvements to optimize cost, schedule and improve the safety of Warfighting capabilities embedded within DoD military aircraft. The paper suggests how to reuse these capabilities during their flight certification efforts across the Aviation fleet resulting in advanced integration schedules and improved interoperability between systems. The paper discusses how these MB processes and tooling are being used today (only in parts) to support the development, verification and validation, and airworthiness certification efforts of complex software intensive CPS, as well as proposes methods for the adoption of such tools within the Government using industry best practices. The paper discusses how MBSE tools and processes can effectively support the management of complex airworthiness processes, and demonstrate to the Airworthiness Authority confidence of proper design implementations of the safe operations of capabilities embedded within avionic systems' components, and safe interactions of inter-dependent components within systems and subsystems typically integrated on aircraft and used throughout the battlespace. These capabilities are needed for safe and effective operations in hostile terrain and all forms of environmental conditions if we are to continue to militarily dominate the battle space of tomorrow.


## INTRODUCTION

The last century's largest developmental change in the aviation community was marked by the transformation from analog to digital -- the "digital transformation". Tomorrow's aircraft's cyber physical systems (CPS) are now 80% software controlled. Technological advances in this digital age have outpaced our ability to timely field systems that remain relevant to support dynamic battlespace requirements. The digital lifecycle of these CPS is shorter than the lifecycle of the host platform. [Dr. Bill Lewis, Director of the AMRDEC's Aviation Development Directorate]


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In addition, the airworthiness qualification efforts of these CPS are notoriously burdened, keeping important capabilities out of the cockpit, capabilities that can assist in pilot, can improve battlespace situational awareness, can enhance safety of flight, and will help maintain our war fighting dominance across the tomorrow's battlespace.

To maintain our edge, improvements in design tools and qualification processes are needed to shorten the digital lifecycle of these CPS through airworthiness so that they can be brought quickly into the fight. Interchangeable robust digital systems are needed for the technological advantage needed to win tomorrow's fight.

A new strategy is needed that incorporates open systems architectures – to break vendor lock, appropriate data rights so all contributing OEM and Platform developers can share designs in cross-organizational fashions, model-based engineering practices and tools, and virtual integration and advanced analyses are critical to speed CPS capability development and fielding. So how do we get "there"?

**When Done is Done**

Dr. Steven Covey's popularly suggested Habits[1] (Ref. 1) tell us to *Be Proactive*, and *Begin with the End in Mind*. Dr. Covey presents an approach to being effective in attaining goals.

If the end goal is airworthiness qualification, then we start with governing policies (Ref. 2, 3), airworthiness guidelines (Ref. 4, 5, 6), standards (Ref. 7 through 16) and end with the scope of qualification objectives that must be demonstrated to the airworthiness authority. That end is likely the RTCA DO-178C objectives (Ref. 4, 7-9, 11-16). That scope ranges from 72 objectives for level-A assurance down to lesser numbers for DAL-B, C, etc. Metrics of completion and level-of-effort (LOE) estimates toward "done" are other key management attributes that must map to these same objectives.

Today's airworthiness qualification practices are notoriously burdened (Ref. 4-6, 13-16), and existing tools used to develop, and verify complex cyber physical systems elude providing us insight into progress toward completion, leaving Program Managers without proper data to manage progress and efforts. If an objective is to have bi-directional linear tracing from high and low level requirements to demonstrated results all which demonstrate progress, then why is so much effort expended on offshoot misaligned efforts that do not participate in achieving these goals?

Lifecycle artifacts, for example, are designed to record proper practices from concept, design, implementation, and provide verification that illustrates direct evidence of the safety and flight worthiness is built into the system. But the result today is unfortunately a bevy of artifacts, primarily paper documents, that is out of sync with the product being built and therefore does not provide visibility into the system engineering and process maturity of an aircraft development. They provide no clear insight into system function and operation or traceability to evidential objectives for airworthiness authorities -- as such these large and costly documents are deemed by program managers to provide little value.

**Figure 1. Static lifecycle products that are out of sync with the product provide little value to Program Managers**

There are 24 to 30+ contract lifecycle documents (Ref. 13, 11, 14) depending on what qualification criteria are being used. For example, shown in the table below, the Army's P&P for LCMC requires 9 plans, 7 specifications, 4 qualifications, and 4 production docs – 24 documents, whereas DO-178C + FACE requires even more, 35 documents. At each lifecycle phase, some sub-set is to be delivered at a stage of document maturity (draft, final, controlled) so to keep record of the development and track progress of the product that is being developed (see Specification of Requirements and Design).

**Table 1. Life-Cycle Document Matrix – document maturity throughout the Life-Cycle Process.**

| | KOM | SRR | PDR | CDR | IPR | TRR | FRR | PRR |
|---|---|---|---|---|---|---|---|---|
| **Program** | **Plans** | | | | | | | |
| SEP | D | F | CCB | | | | Key | |
| SEMP | D | F | CCB | | | | D | Draft |
| SDP | D | F | CCB | | | | F | Final |
| SCMP | D | F | CCB | | | | CCB | Controlled |
| SQAP | D | F | CCB | | | | | |
| SSPP | D | F | CCB | | | | | |
| SwSPP | D | F | CCB | | | | | |
| SVVP/TEMP | D | F | CCB | | | | | |
| IMS | D | F | CCB | | | | | |
| **Specification** | **Rqmts** | **Design** | | | | | | |
| SSS | D | F | CCB | | | | | |
| SSDD | | D | F | CCB | | | | |
| SRS | | D | F | CCB | | | | |
| HwRS | | D | F | CCB | | | | |
| IRS | | D | F | CCB | | | | |
| SDD | | | D | F | CCB | | | |
| IDD | | | D | F | CCB | | | |
| **Qualification** | **Testing** | | | | | | | |
| STP | | | D | F | CCB | | | |
| STD | | | | D | F | CCB | | |
| SVD | | | | | D | F | CCB | |
| STR | | | | | D | F | CCB | |
| **Production** | **Install** | **Manuals** | | | | | | |
| SVD | (above) | | | | D | F | CCB | |
| SPS | | | | | | D | F | CCB |
| SIP | | | | | | D | F | CCB |
| SUM | | | | | | D | F | CCB |

[a] PM Aviation Systems Aviation Mission Equipment Systems Engineering Process and Procedures for Life-Cycle Management Command Acquisition (Ref. 13)

[1] The 7 Habits of Highly Effective People, Stephen Covey, Free Press 1989

For example in the US Army's LCMC 24 documents are required, Table-1. At KOM a draft of 9 plans are required. At CDR, 9 documents are to be delivered in various stages of document maturity, i.e., 6 specification docs, 2 qualification docs, and 1 production document.

What is the value of, for example, a static signed version of a SRS from the design phase and CDR milestone review, once it is resolved in the later integration and testing phase that one customer requirement was written incorrectly (several months earlier)? Once the detrimental issues of that requirement are identified, confirmed to be incorrect, and approved for correction; all design and implementation related to that requirements must catch-up. The value therefore lies in the corrected artifact that represents the current state of the dynamically developing product, not the out-dated misaligned records of a now revised product.

So how can MBSE processes and tools help?

## A VISION – UNIFIED PRODUCT DEVELOPMENT, AND CHANGES NEEDED

### Artifact Engineering

The change needed is artifact engineering (Ref. 26, 19), where the process of the design, development, and integration of the product must include unified documentation of the current state of that product. There should be no longer the act of reallocating 2-3 resources off of development activities to back-fill lifecycle artifacts for next month's programmatic milestone review (PDR, SRR, CDR, TRR), Table-1.

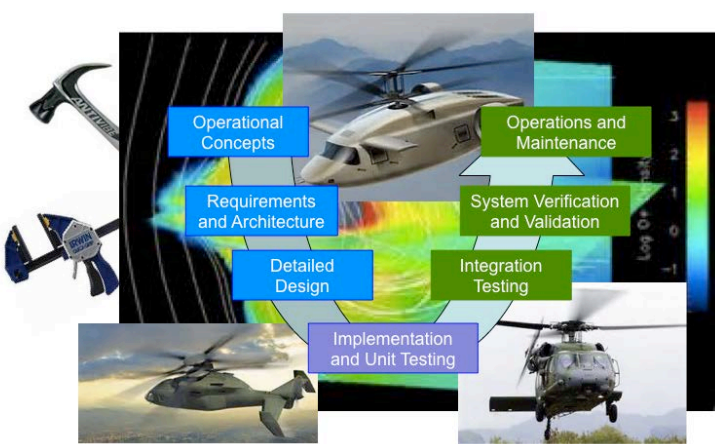


**Figure 2. Verification, Validation and Accreditation of MBSE Simulation and Tools, Innovation and Modernization Projects Affecting Capabilities and Technology (IMPACT): The Airworthiness of Complex Systems, Final Report v1.0, US Army Aviation Development Directorate (ADD), 2015 (Ref. 19)**

### Role-based cross-organizational modeling capabilities

Correspondingly another change needed is role-based cross-organizational modeling capabilities, where teams of systems engineers, programmers, testers, and of course Program Managers, Technical Chiefs, and those too often back-end airworthiness authorities, all have visual insight to the current state of the product. Collectively, they have visibility to and toward the current completion of the 72 objectives; visibility to what is done, and equally important, what is not done.

As a result, team program/product reviews are conducted in real-time, and are recorded as percent complete metrics. Who has worked on (insert software module name here) part/module of the system, who has checked that work (that it technically meets requirements, and implementation conforms to design standards and styles), who has authorized to approve completion, and as important, who hasn't? At last we will have insight and it will become wholly apparent to who on the integrated product team (IPT) is *rowing well* and who needs to *row* harder to keep progress moving toward objective achievement on time and on schedule.

**Figure 3. Role-based modeling capabilities will provide insight toward completion**

### Role-based Model-Based Tooling will allow us to Embrace Change, Embrace Correction

Everyone has at one point furnished an interior room. We try, look, see, move a bit, repeat. Development lifecycles must be recognized as dynamic cyclic processes. Best attempts are made to capture requirements, but it is often not until you "see" that "it" is deemed "right or wrong". Notoriously burdening (e.g., milestone authorization signatures on large complex documentation developed within a linear top-to-bottom "waterfall" process), change is shunned.

However, opportunities abound with role-based model-based tooling which will allow us to embrace change, efficiently identify errors and embrace corrections early in the lifecycle when they are less costly to correct. And as soon as a model-based systems-of-systems implementation provides visibility and insight that a requirement may be incorrect, then the requirement can be authorized for change, and the change begins affecting only that part of the system until it is back inline with the lifecycle phase (that is it reverts back to SRR phase). Team members as well as Program/Product Managers want a properly functional system, so lets not have a lifecycle approval process that inhibits correction.

### The CPS Dashboard – when Done is Done, or Done Done

The authors have conducted studies mapping the 72 DO-178C table objectives to lifecycle artifacts required for qualification process (Ref. 4, 11), and have resolved several process improvements that can serve to enhance the development lifecycle experience, improve product and safety, reduce schedule and cost through sustainment of fielded product.

Additionally, when applied to model-based techniques, open systems architecture standards (e.g., FACE™, HOST, etc., Ref. 15, 16), product portability and reusability benefits abound, with projections that 90% of the objectives can be leveraged, leaving 10% to be demonstrated on the ported target [see the yellow highlight table objectives in the figure below].

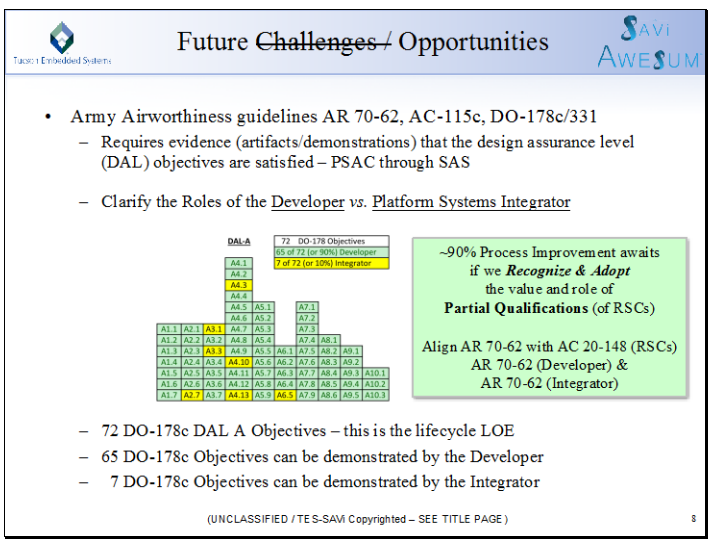


**Figure 4. Presentation, "Future Challenges (Opportunities) of (for) Systems Engineers, Model-Based Systems Engineering (MBSE) Developing and Qualifying FACE™ Open Systems and Applications onto US Army Aviation Systems", SoSE&I 2015 Senior Acquisition Engineering Leadership Workshop, 20 August 2015 (Ref. 17)**

## IMPEDIMENTS AND SUGGESTIONS

### Open Systems versus Proprietary -- break vendor lock

Advanced embedded avionic systems are complex and that complexity will increase. No longer can one development team (read OEM organization) develop alone our next generation aircraft weapon systems. Enhanced capability and the pace of change will require that the best-of-best replace last week's best in order to maintain warfighter and battlespace dominance.

As such, OEM development silos are gone; so today's DoD business practices require revisions to promote multi-organizational development and leverage product reuse across a fleet of aircraft. A parallel challenge will be overcoming the reluctance of large OEM organizations breaking up the job security of these OEM silos, and their reluctance toward sharing proprietary component designs of systems and systems-of-systems with other competitive organizations.

### Model-based Data Modeling

The answer to organizational sharing shall evolve as model-based data modeling practices mature, as tools for data modeling implementation become readily available, and as data modeling becomes accepted as a secure practice for organizations sharing their contributions of proprietary design efforts to a larger systems-of-systems multi-organizational aircraft design. Data modeling requirements expose details of interface designs, hint at but sufficiently hide internal implementations. Open systems standards efforts, namely the Open Group's Future Airborne Capability Environment (FACE™) (Ref. 15, 16) are defining data modeling interfaces to promote reuse and interoperability of capabilities, and data model design tools are just now reaching the market [e.g., TES-SAVi's FAME™, http://www3.opengroup.org/face/third-party-tools ].

### When Partial Qualifications become recognized and Capability Reuse becomes accepted common practice

Secondly, while there are DoD directives for software reuse (Ref. 2, 3), what is needed are simply stated acquisition vehicles to encourage the development of reusable software components (RSC) AC 20-148 (Ref. 8) in a target platform PM leader-follower role. That being one DoD aviation Platform takes "lead" in acquiring a common reusable capability. A "lead" capability developer is contracted for developing to RSC guidelines (Ref. 8, 15). They are optionally contracted (contract + options) and may benefit with follow-on efforts to port that software capability and qualify that capability on other DoD aviation platforms/target systems (Ref. 22).

Hampering this reuse advance, besides as mentioned DoD acquisition, is the accepted and recognized practice of partial qualification efforts. Only then will reuse become a reality that benefits the developer, acquirer, and enhance capability interoperability of the battlespace. Only then will a 90-10 benefit be realized, and costs and schedules for the airworthiness of complex CPS be reduced, and made more affordable in today's demanding military budget limits. We can be in position to row more efficiently and move faster with safer and more secure battlespace capabilities.

**Figure 5. Standards-based reusable products designed for Open Systems Architectures will speed capability integration schedules and improve interoperability across a fleet of aircraft**

Many of these aforementioned gaps in tools and processes were identified during IMPACT (Ref. 19), and some focused ADD S&T funding [e.g., AVCIP] have begun to fill these gaps. Model-based capabilities are believed to be the answer to plugging these gaps and enhanced MBE tools that can manage the lifecycle data of complex CPS components, systems, and systems-of-systems developed by inter-discipline roles and across organizational boundaries.

**Figure 6. Model-based tools that can support role-based cross-organizational modeling capabilities are needed for next-generation systems-of-systems aircraft design efforts**

The clock ticks down to when these next-gen tools and processes for the development and qualification of airworthiness complex CPS are required for the Future Vertical Lift Family of Systems (FVL FoS), scheduled for 2020 timeframe [ADD Industry Days – 20, 21, (Ref. 20, 21)].

The FVL FoS goal is a complete replacement of the current fleet of aviation platforms. The requirements are formulating by class of aircraft weapons systems. The need for speed, zero maintenance, and manned unmanned teaming (MUMT) of battlespace assets operating in all weather, visually impaired obscurant conditions, within complex terrain will be the exciting tasks of the Aviation community. (Ref. 20, 21). "At no other time in aviation history have so many challenges been placed on the community of developers." [AMRDEC Director, Dr. Bill Lewis, ADD Industry Days, Ref. 20, 21].

**Yesterday's Every Solider is a Sensor, is now MUMT at the speed of flight**

Indeed, enhanced MBE tools supporting efficient airworthiness processes and new DoD business practices will reshape today's paradigm. The 1990's concept of Every Soldier is a Sensor (ESS) is now expanded to -- every platform is a sensor traveling at the speed of flight over the battlefield carrying with it a part of a distributed sensor suite collecting data to formulate an aggregate of safety-of-flight maneuvers, supporting engagement and targeting. Furthermore, this next-gen battlespace must be built safely and securely from cypher attacks. It must operate across dynamic areas of operations, it must operate Jointly IFF, and it must operate over the rise-and-fall of turmoil and disruptions within civilian airspaces. The single smart weapons of today will become a collaborative decisive battlespace of weapon systems reaching 500 Km square connected by dynamic network of secure communications and speed of flight data sharing.

**Advance Modeling to Own the ~~Night~~ Environment, aka 3+9**

Our next-generation aircraft will be required to own the environment (Ref. 20, 21). How do we sufficiently demonstrate progress toward airworthiness of complex systems under austere environmental conditions (snow, rain, fog, smoke, brown-out, etc)? Specifically, Figure-2 shows t7 DO-178C table objectives that require demonstration of operations on a target platform.

The answer lies within, again, MBSE combined with advanced system architecture virtual integration simulations of CPS in controlled laboratory environments (Ref. 32, 27, 28). With advanced MBE tools and analyses we can add into simulation physical interactions of real-world/simulated weather and environmental conditions to test and evaluate the performance of CPS under austere conditions in the lab environment (Ref. 25).

During a previous AHS international conference 2013 (Ref. 25), the Authors were approach by SOCOM, identifying that with such a capability, they could use operational simulations for mission planning and conduct mission rehearsals. They could review results, exchange system configurations of mission packages virtually, re-run the simulation, and optimize the mission success by varying known/unknown hostile, complex terrain, environmental, and austere weather conditions.

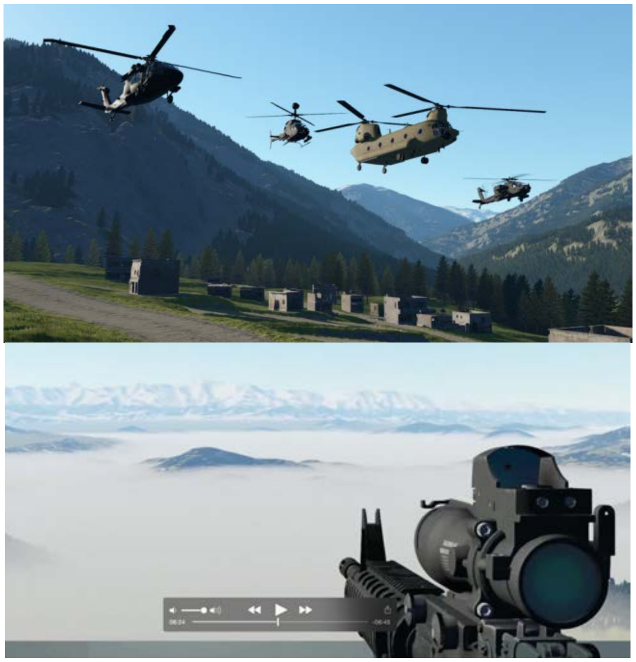

**Figure 7. Platform Simulations Network-Centric Operations using MBSE, demonstrated at FACE™ Tucson Member's meeting, 2013; and simulated DVE - Own the Environment - MBSE TES-SAVi simulation capabilities within AWESUM™**

SAVI and simulated fleet of US Army aircraft allows us evaluate performance of embedded FACE™ aligned software of CPS ported to dissimilar target architectures. It is hopeful that such simulations will be acceptable demonstrations of requirements for airworthiness for the operations of complex systems under austere environment requirements. Additionally, such SAVi simulations are attractive for mission planning and optimizing mission payloads and mission rehearsals to enhance mission success for operations under difficult terrain, hostile, and environmental conditions (Ref. 25, 27).

**Is MBSE only valuable to the military investors?**

These technologies also have great promise for marketing sales and distribution of civilian marketplace as well as NASA space exploration. It boils down to the management of develop of complex systems of systems and the Manned and UnManned Teaming (MUMT) of these complex interdependent operations. This is akin to the refinement and transition of Henry Ford's assembly line to into the robotic age. Today not all operations are manned; some are efficiently machine-stamped and machine assembled. Whereas product design remains a creative manned process, the development, manufacture, and delivery processes stand to benefit from automation. Today's complex aircraft and cyber physical systems are 80% software. MBSE tools assist to properly manage the voluminous data required to sufficiently design these CPS, systems, and systems-of-systems. Code generators will play heavily in the software robotic age supported by model-based systems engineering (MBSE) practices and model-based engineering (MBE) tools.

**From CPS components to Systems and Systems-of-Systems – Resourcing Issues**

As identified during the SOSE&I workshop conducted by the OSD ASA/ALT in 2015 (Ref. 17), there is a growing need for systems engineers to assist with the designs of our next generation of aircraft. Enhanced model-based capabilities will naturally lead us to perform high-order analyses of systems and systems-of-systems.

CPS will be designed as components, tested and partially qualified for airworthiness efforts, and added to a system diagram palette. Engineers will drag-and-drop CPS components and design architecture systems. MBSE tools will allow us to auto-generate control code and tests, and advanced analyses packages (Ref. 28) will allow us to conduct performance evaluation against these systems earlier in the lifecycle. This provides to MBSE users the ability to conduct system trade studies to optimize architecture design and performance.

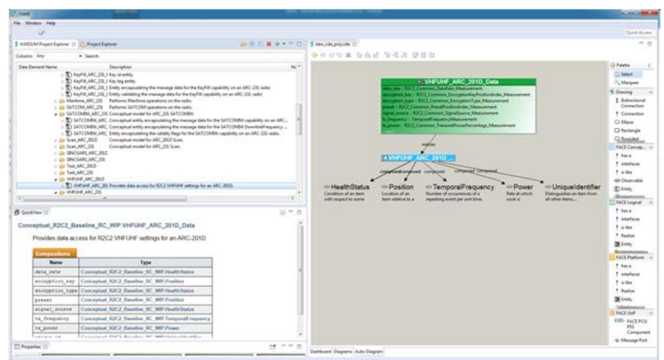

**Figure 8. TES-SAVi's FAME™, a FACE™ Architectural Modeling Environment, 2016**

The need is for experienced systems engineers with aviation backgrounds, skilled users of latest MBSE tools and processes. Educational institutions, like the University of Alabama in Huntsville (UAH) are poised to address this need; others include Georgia Tech, University of Maryland, Penn State University, and Software Engineering Institute Carnegie Mellon.

The UAH Rotorcraft Systems Engineering and Simulation Center is on-track bringing into its labs the latest industry and academic MBSE tools, training students to these advance systems, and building-out capabilities to further enhance them. Graduates with such hands-on MBSE experience will be of value to employers and stand-ready to fill a resource gap and help the aviation community design the next generation of systems-of-systems CPS complex aircraft worldwide, both military and commercial. MBSE and MBE tools and processes are indeed enablers for progress within the aviation community.

**Promising Efforts**

Tucson Embedded Systems, Inc.'s TES-SAVi has developed and is using AWESUM™ a MBE lifecycle tool to create and support the qualification efforts of CPS (Ref. 22-26, 19, 17). We are "working with" early adopters of MBSE in collaborative team development environments and investigating how we can optimize the resources needed to bring advanced capability to systems-of-systems faster, pushing the envelope of current business practices, mindful of OSA standards (e.g., FACE™), product line reuse, and safety and security of systems and sensitive data. We are S&T funded to evaluate how we can develop advance systems that can provide on-board and off-board data to ensure safety of flight (Ref. 25), improve flight performance, reduce fatigue thereby extending service life of systems and platform. We are working to the 2050 Vision described by ADD [Dr. Bill Lewis (Ref. 18-21) by building next-gen MBSE process and tools for airworthiness.

## CONCLUSIONS

Tucson Embedded Systems (TES) & TES-SAVi have worked along side of US Army Aviation developing concepts, streamlining processes for common reusable military software and products to be used and reused across the current fleet of disparate aircraft (manned and more recently unmanned) for the past decade (Ref. 22-26). These efforts have led us to the development of a MBE tool suite, AWESUM™ (Ref. 26), that is positioned well to support the needs for next-generation Future Vertical Lift Family of Systems (FVL FoS) development and operational needs and advanced studies.

The Authors are excited to continue contributing to the AHS body of knowledge, and supporting the Aviation Community with advanced tools that can support the next-generation of air weapons systems development, efficient fielding, and sustainment.

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