System Architecture Virtual Integration

SAVI AFE 59S1 Report

Summary Final Report

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EXECUTIVE SUMMARY

The objectives of this phase of the System Architecture Virtual Integration (SAVI) development effort concentrated on two shadow (meaning they were to be conducted alongside real world development efforts) projects [3, 4] that utilized the prototypical SAVI VIP that had evolved during previous Proof-of-Concept (PoC) stage. The first of these shadow projects, the Aircraft Monitoring System (AMS), was generated as a cyberphysical development typical of integrated hardware/software systems supplied to original equipment manufacturers (OEMs) by a Tier 1 supplier, and though both elements were typical of such systems, there was no full-up work on an AMS ongoing during the term of this work. The AMS included two primary subsystems, a vibration monitoring element and an element to monitor the safe latching of aircraft doors. The second shadow project was a considerably more complex aircraft subsystem that was being upgraded as part of a contract with the U. S. Army Aviation Center in Huntsville, AL. This project is a significant modification to the Common Avionics Architecture System (CAAS) on the CH-47 Chinook helicopter. These two shadow projects presented two very different types of systems development as a means of closing out the SAVI PoC work. The SAVI team representatives converted the Army's proprietary architectural model for this effort into a generic set of models made available to all SAVI participants and documented the lessons learned.

The goal of the AMS shadow project evolved into a demonstration of managing the complexity of integrating various systems into one aircraft platform by international participants. The mechanics of cooperation in standing up the repository infrastructure and defining the virtual integration model framework became the focus of the member companies. Mechanisms developed to separate public model data from a supplier's private, proprietary data were of most interest. Existing SAVI use cases were exercised where applicable, and new use cases were developed based on issues that arose during this shadow project.

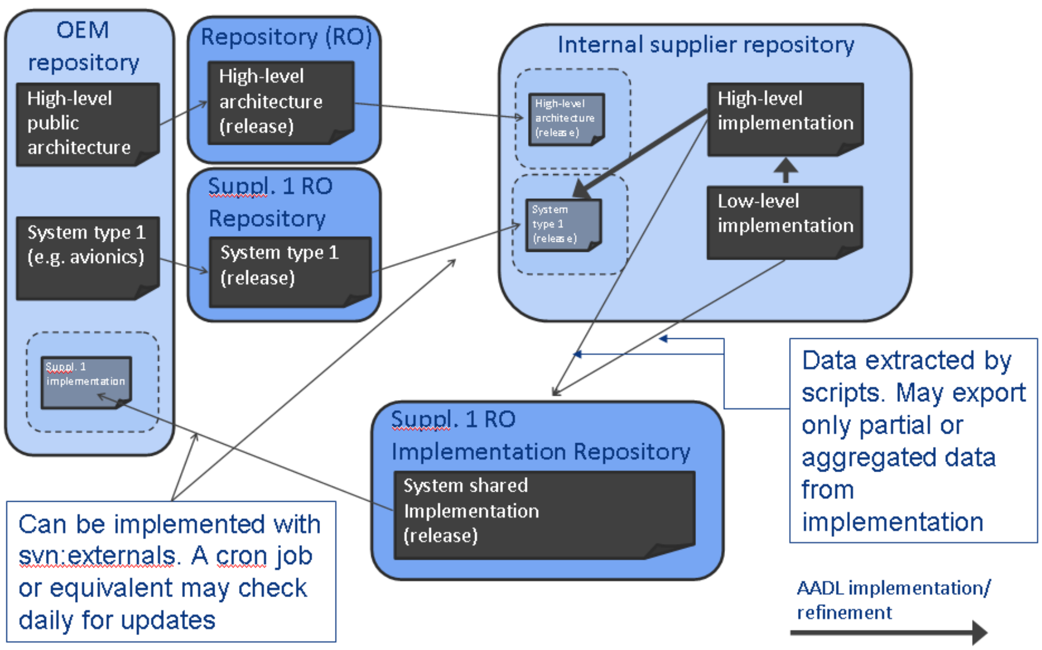

Figure 1. Typical supplier repository structure for AMS.

The following requirements/constraints were postulated for the AMS repository structure developed.

1. Each company may have a different shared interface with each of the other companies (or customer, authorities etc.);

2. Any party may choose to pass only a simplified model to the other party (OEM-supplier, supplier-supplier, supplier-OEM, etc.);
3. Each party has its own configuration management policy and cycle;
4. The configuration management policy should not be fixed for a given party. It is considered that this may change with every program;
5. The update of a model shared with another party must be a formal procedure, under configuration management (akin to a software release);
6. The ownership of information must be clear, in two senses:
    a. The owner of the IP must be always defined;
    b. The company allowed (and responsible) for changes must be always well defined.

Unfortunately, not all of the goals of the original AMS shadow were met during AFE 59S1. The increased scope of the project reflected real world product and development complexities that SAVI is designed to manage. The team spent considerable time investigating and solving issues associated with setting up an international infrastructure to support the cooperative effort. Thus, the deliverables from this program serve as a demonstration of feasibility of the SAVI modeling approach in a real world application. It is most unfortunate that the results of this activity were not able to identify specific benefits of the AMS shadow SAVI structure compared to an actual development program.

The U.S. Army wanted to apply the SAVI VIP to an actual project. An AADL model of the CAAS architecture, developed by Rockwell Collins and maintained for the Army by Dr. Peter Feiler at SEI, already existed. The original intent was to obtain Army approval to publicly release a version of this model and associated documentation so that the data would be openly available, thus allowing any SAVI member to participate in the shadow project and subsequent model development. However, the Army was not able to approve the model and documentation for publication, so the CH-47 shadow team developed an alternate execution plan. The Rockwell Collins SAVI team developed the models and provided them to Dr. Feiler, who created a generic version suitable for public release.

Since many SAVI member companies use the OMG (Object Management Group) SysML architecture modeling language, the CH-47 CAAS Upgrade shadow project incorporates a SysML model into the SAVI VIP. The DARPA-developed META SysML-AADL translator maintains two-way synchronization between the SysML and AADL models. Enhancements to the publicly available META translator were provided to SAVI members.

The RoI estimation effort concluded during AFE 59S1 by adding and demonstrating capability to incorporate hardware elements with a commercial software product (SEER-H from Galorath, Inc.). The resulting costs were examined in comparison to previous work and largely confirmed that the SAVI estimates are all consistent. These predictions still indicate that the development cost for SAVI is regained through use in just one major aircraft program.

Outreach efforts continued with a large number of presentations to communicate to the industry, and particularly to potential SAVI members, the value of the SAVI approach and our progress toward implementing this paradigm shift. SAVI added the first Tool Vendor Partner (Esterel Technologies) during this period.

Finally, the Integrated Program Plan has been modified and update to reflect recent decisions about how to proceed with the incremental development. This plan has also been expanded to include a broader array of definitions and draft operating procedures.

REFERENCES

Note: All SAVI AFE 58 documents (numbered and titled) are found on the SAVI AFE 59 Sharepoint web site at:
System Architecture Virtual Integration > AFE 59 - Expanded PoC Demonstration > AFE 58 Documents
All SAVI AFE 59 documents are found on the SAVI AFE 59 Sharepoint web site at:
System Architecture Virtual Integration > AFE 59 - Expanded PoC Demonstration > AFE 59 Documents

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INTRODUCTION

1.1 Heilmeier Catechism Applied to Systems Architecture Virtual Integration

George H. Heilmeier became the Director of the Defense Advanced Research Projects Agency (DARPA) in 1975 after making significant contributions to a number of important electrical engineering projects in the early stages of his career (notably, tunnel diode down-converters, millimeter wave generation, ferroelectric thin film devices, and organic semiconductors). In 1964 his research led to the first working liquid crystal displays based on the principle he called the "dynamic scattering mode" (DSM). He and three of his colleagues received the 2012 Charles Stark Draper Prize from the National Academy of Engineering in 2012 for this work. While at DARPA he and the agency delved into low observable technology for aircraft, space-based lasers and infrared technology, and artificial intelligence.

While at DARPA, Dr. Heilmeier also promoted the use of a famous set of questions, which became known as the "Heilmeier Catechism", in reviewing and evaluate research proposals. A concise form of this set of key questions is listed below, reputed to have come from Heilmeier's lecture "Some Reflections on Innovation and Invention" when he received the 1992 Founders Award from the National Academy of Engineering[1]:

- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What's new in your approach and why do you think it will be successful?
- Who cares?
- If you're successful, what difference will it make?
- What are the risks and the payoffs?
- How much will it cost?
- How long will it take?
- What are the midterm and final "exams" to check for success?

Applying these principles to SAVI's Virtual Integration Process, suggests the following questions and answers.

(1) *What is SAVI trying to do?* The SAVI VIP is meant to "Integrate – then Build" as opposed to the as-is approach of waiting to check the engineering consistency of system elements until these elements are nearing physical and logical completion. Perhaps a better catch phrase for SAVI is "Integrate, Analyze – then Build", since this phrase better captures what the VIP is designed to do.

(2) *What Is New in the SAVI Approach? And Why Is It Likely to Succeed?* The VIP leverages the latest advances in architecture-centric modeling to repeatedly evaluate all interacting components (both hardware and software) of the proposed system. These analyses are choreographed by the annotated architectural model that allows discipline engineers to use familiar analysis tools to support these early and frequent evaluations. This form of analytical consistency checking allows the VIP to find and correct requirements deficiencies, coding anomalies, and incompatible corrections significantly earlier in the development process than the as-is integration process does.

(3) *Who Cares? What Can SAVI do for You?* Every major participant in the development process stands to gain from the SAVI VIP. While the System Integrator likely gains the most, any player with a significant stake in the integration process should profit handsomely from applying the SAVI VIP. A recent RoI estimation showed that any supplier responsible for integration of 5000 lines of source code on a new commercial airplane system would likely show at least 4% RoI annually. The SAVI team has evolved (and continues to do so) a cost/benefit estimate that predicts very positive annual Return on Investment for both major suppliers and OEMs. Using conservative assumptions and reviewing results with cost estimation experts within participating organizations, these estimates are carefully vetted indicators of what SAVI can do for system developers.

(4) *If SAVI Is Successful, What Difference Will It Make?* When the SAVI VIP becomes the preferred way of integrating complex, software-intensive systems, aerospace developments should take less time and complete with reduced costs. Finding defects and anomalies sooner with early-and-often consistency checking should guarantee these two gains. The SAVI team believes the VIP is the most-needed in a series of potential MBSE improvements that will allow our industry to cope with more complex systems in the future.

(5) What Are the Risks and the Payoffs? The biggest risk that the SAVI VIP addresses is that the industry will be unable to affordably develop more complex systems. The business case for developing new commercial airplanes within the current system development construct is becoming harder and harder to make. To be sure there is significant cost and time associated with developing SAVI concepts. This part of the risk can be mitigated significantly by cooperatively sharing the burden within the entire industry, as practiced by the AVSI model of research cooperation. It is quite unlikely that any single SAVI participant can readily accept the total cost of development; yet the industry cannot afford to continue to operate with the same integration philosophy used in the past. The payoff in the SAVI approach is shared cost and an industry-wide solution that is influenced and accepted by regulatory agencies.

(6) How Much Will It Cost? Can You Afford It? Current cost estimates (and they have been stable for approximately three years) project a development cost of approximately $86 million dollars for a SAVI VIP that is ready for use in developing a new commercial aircraft. This cost is based on a process that is matured by application of the VIP at each hierarchical level to representative, real-world systems and subsystems so that at the end point a program manager will not need to accept additional risk due to immaturity of the VIP. Use of SAVI at the end of this development cycle should be overall reduced risk in terms of cost and schedule rather than increased risk. At the end of this development, perhaps instead of the second question above, the proper query is: *Can you afford not to use the SAVI VIP*?

(7) How Long Will It Take? What Does SAVI Need to Make a Difference Now? The most up to date SAVI Roadmap anticipates completion of development in 2019. This projection is based upon a protracted incremental development made necessary by the economic downturn that started in 2008. The SAVI team believes that with adequate support a full-up SAVI capability could be demonstrated by 2016, but that compression will require doubling the commitment of current members and adding at least nine new participants immediately – both considered to be highly unlikely. However, we expect to field a limited capability, not a mature one, within the next two years, even following the current plan with limited resources to accelerate SAVI development.

(8) How Can We Check SAVI Progress? The current incremental development plan offers ample opportunity for evaluating regularly SAVI progress and a metric similar to the NASA-generated Technology Readiness Level will be used to measure overall progress. Moreover, two shadow projects are currently underway that will allow direct analysis of the value of the SAVI VIP. More such parallel projects are planned and the incremental development approach used so far leaves a clear trail written reports that detail progress in the development and areas needing more emphasis.

1.2 Expanded Proof-of-Concept (EPoC) Shadow Project Demonstrations (AFE 59S1)

1.2.1 First Shadow Projects.

The last phase of the SAVI EPoC demonstration concentrated on the first two “Shadow Projects” undertaken by the SAVI team. These efforts, supplemental to AFE 59 and its predecessor AFE 58, explored prototypical applications of the SAVI VIP with two types of development efforts. First, a project built around subsystem for an entire airplane was sought. One of our members, the Goodrich Corporation planned such an effort to create a vibration monitoring subsystem to be installed within a health monitoring system aimed primarily at helicopter applications. Later, a door monitoring subsystem was added to this effort and this shadow project became an Aircraft Monitoring System (AMS) [3]. A second, more ambitious, project was proposed by the U.S. Army; this

"Shadow Project" was a significant upgrade to the Control Avionics System (CAAS) for the Army's CH-47 Chinook managed by the program [4] office from Redstone Arsenal at Huntsville, Alabama. Not only was this effort a larger project in scope, it was also mostly a contracted effort through the primary avionics contractor Rockwell Collins and much of the work was proprietary. Consequently, the SAVI team working this second shadow project provided a set of generic models that could be shared with all participants to guarantee the SAVI development profited from this exercise and that lessons learned were communicated to all SAVI participants.

1.2.2 EPoC Shadow Project Objectives.

The EPoCD Shadow Project objectives are spelled out in considerable detail in the governing document [2]. They are summarized under ten task statements below.

Task 1: Plan a "Shadow" Structure to Monitor Development Projects

This task lays out a plan and an organizational structure to allow comparison of the SAVI VIP to real world development efforts. This structure includes a SAVI evaluation of project requirements and follows the actual development as closely as possible. It also allows quantitative assessment of project milestones and intermediate objectives at each level of the hierarchy. An AADL description of the actual development highlights those points where the SAVI VIP leads to earlier identification of problem areas.

Task 2: Broaden the Use Case Demonstrations to Satisfy Needs of "Shadow" Programs

The programs to be "shadowed" will undoubtedly need Use Cases not considered during AFE 59. This task must identify those elements of the programs to be shadowed not covered by Use Cases exercised earlier. In addition the Use Case Demonstrations performed earlier may need modification and additional analysis to make them useful to the "shadow" programs. Activities (subtasks) to be performed include:

a. Identify Needed New Use Cases to support Shadow Projects of Task 1
b. Spell out Appropriate Modifications to Existing Use Cases

Task 3: Continue the Development of Use Case Demonstrations to Further Populate Core SAVI Version 1.0 Requirements

To prepare for the next phase of SAVI development, the PMC anticipates that additional Use Cases need to be exercised over and above the four sets exercised in AFE 59 and those additional ones needed for Shadow Projects 1 and 2 of Supplement 1 (Task 2a above). Moreover, the lessons learned from these Use Cases must be incorporated in the structure of the MRDEL for SAVI Version 1.0 to provide useful, though limited, capability to real world developments.

a. Identify, prioritize, and exercise Use Cases deemed essential for SAVI Version 1.0
b. Analyze Use Case results and modify the SAVI MR/DEL requirements for SAVI Version 1.0 implementation

Task 4: Evaluate ADL/IDL and Multi-Language-Model Approaches Best Suited for SAVI Development

This task addresses whether AADL is an appropriate starting point of an ADL/IDL for the long-range development of the SAVI VIP, and whether a multi-language-model is a better approach for the SAVI repository. Activities (subtasks) to be performed include:

a. Identify requirements necessary for the SAVI ADL/IDL
b. Evaluate, candidate ADLs/IDLs based on the requirements spelled out in Task 4a
c. Develop an analysis framework for multi-language-model evaluation.
d. Perform multi-language-model evaluation.

Task 5: Implement a "Shadow" Concept for at Least One Development Project

This task carries out the plan evolved in Task 1, exercises the organizational structure from that Task, and collects and analyzes data to compare the SAVI VIP's predicted gains to real decisions made in specific development projects. This work provides the primary results sought from AFE 59S1.

Task 6: Update the RoI Analysis Methodology

a. Add capability to model effects of physical hardware to the SAVI RoI Estimation Tool (SRET).
b. Improve usability of the SRET.
c. Capture effects of Shadow projects on RoI analysis estimation.

Task 7: Identify and Coordinate with Additional SAVI Stakeholders Including Potential SAVI Participants

AFE 59 fell short of its goal of adding two additional members during its first phase, even though the membership did include two more participants than participated in AFE 58. Consequently, this base of support is still less than the size needed to pursue overall SAVI goals as rapidly as had been planned in the AFE 58 Roadmap. Moreover, there are still critical areas where the needed specialist skills are in short supply: for example, SAVI still has not attracted the software developers needed to insure that analysis tools and architectural definitions can interface with one another completely.

Furthermore, it has been recognized since the AFE 58 effort that development of full SAVI capability will rely on working with existing efforts throughout the global aerospace and defense industry. SAVI seeks to avoid duplication of effort and expects to leverage existing and emerging technologies as much as possible. Thus this task includes a range of outreach activities intended to publicize the SAVI effort to sympathetic stakeholders in order to develop new SAVI members and SAVI non-member partners.

a. Update Plan and Aggressively Pursue New Members for the SAVI Project
b. Publicize Results from the SAVI Effort

Task 8: Write AFE 59S1 Final Report and Supporting Documents

This task includes writing, revising, and approving a summary final report along with supporting documents deemed necessary by the PMC.

a. Choose AFE 59S1 Data Deliverables Deemed Necessary to the SAVI Effort
b. Write/Approve Supporting Documents
c. Write/Approve Summary Final Report

Task 9: Manage the AFE 59S1 Project and Update the SAVI Integrated Program Plan

This task includes all project management tasks deemed necessary by the PMC and AVSI management.

a. Continue tracking all AFE 59 tasks
b. Prepare and obtain approval for a revised SAVI Integrated Program Plan (IPP)

STRUCTURE OF EPoC SHADOW PROJECT DEMONSTRATION EFFORT

The work flow for each of the 9 tasks and task interactions are shown in Figure 2, along with an indication of the responsibilities of each Working Group.

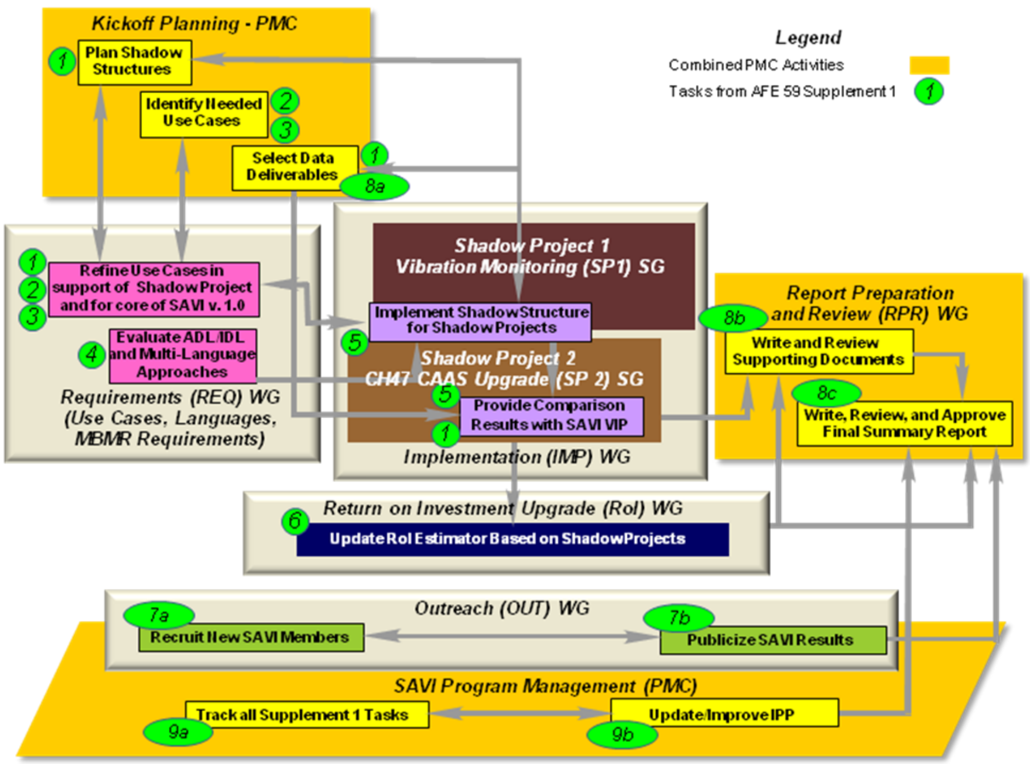


Figure 2. Work flow and task interactions for AFE 59S1.

2.1 Program Management Committee (PMC)

The SAVI management structure is typical of AVSI projects with a representative from each participating organization holding voting rights as spelled out in the AVSI Cooperative Agreement [5]. For this AFE the members of the Program Management Committee (PMC) are listed in Table 1. Liaison members are shown with an asterisk.

Table 1. SAVI PMC membership.

Organization	Voting Member	Type of membership
Airbus	Laurent Duffau	Industry (full participant)
Boeing	John Chilenski	Industry (full participant)
Department of Defense	Bruce Lewis	Government (full participant)
EMBRAER	Rodrigo Starr	Industry (full participant)
Federal Aviation Administration	Srini Mandalapu	Government (Liaison member)
Goodrich	Bernie Dion	Industry (full participant)
Honeywell	Jeff Hanson	Industry (full participant)
NASA	Kurt Woodham	Government (Liaison member)
Rockwell Collins	Greg Pollari	Industry (full participant)

2.2 Outreach (OUT) Working Group

As suggested in Figure 2, the work to be done in each of the tasks was carried out in smaller working groups manned by individual participants. Each organization chose the working groups in which to be active at the beginning of the project. The first of these groups, a continuation of what was called the Growth, Communications, and Expansion (GCE) Working Group (WG) during the previous phase of development, was responsible for communicating (both with the rest of industry and internally) the SAVI message. It is the primary objective of this WG to promote growth of participation in the SAVI program, ultimately to a size of approximately 22 participants [6] with the appropriate skill sets to allow completion of the SAVI development.

2.2.1. OUT WG Members and Structure.

There were four organizations associated with the OUT WG and the members who worked this effort continuously throughout the period of performance were AVSI (David Redman, WG Chairman, and Don Ward); DoD (Bruce Lewis); and Rockwell Collins (Greg Pollari and Jean Claude Lebraud).

2.2.2. Efforts during AFE 59S1.

The OUT WG continued efforts to expand the SAVI team during this period of Performance with a strong set of SAVI Seminars and with a number of presentations at strategically selected locations. Specific presentations were given to member organizations that requested them to shore up internal support as well.

SAVI presentation audiences included:

- Industry conferences carefully chosen to help spread the influence of the SAVI concept.
- Several groups affiliated with the SAVI team with particular attention paid to the United States Department of Defense.

2.3 Implementation (IMP) Working Group

The second WG, the Implementation WG, was the core group tasked to see that the chosen shadow projects were completed. This WG broke up into two subgroups, one to pursue the Aircraft Monitor System (described more completely in Section 4.1) and one to work with the U. S. Army program office working on the CH-47 Common Advanced Avionics System (CAAS). There were significant differences between how these two subgroups approached the tasks assigned to them.

2.3.1. The Aircraft Monitoring Subgroup (AMS) Members and Structure.

The AMS Subgroup consisted of Goodrich (Bernie Dion, Chairman), Airbus (Laurent Duffau and Patrice Thiebaud), Boeing (Michael Kerstetter), EMBRAER (Rodrigo Starr), Honeywell (Jeff Hanson and Ajit Shemoy), and Rockwell Collins (Greg Pollari and Kirschen Seah).

2.3.2. The CH-47 CAAS Subgroup Members and Structure.

This Subgroup's efforts for the CH-47 CAAS Upgrade effort was largely carried out within the U. S. Army program office and the Rockwell Collins team that was under contract to the Army's development effort at Redstone Arsenal. However, the SAVI CH-47 CAAS Subgroup was represented strongly in the effort through Rockwell Collins (Greg Pollari, Co-chairman, and Kirschen Seah) and DoD (Bruce Lewis, Co-Chairman, and Peter Feiler from SEI). These individuals converted the Army's proprietary architectural model for this effort into a generic set of models made available to all SAVI participants and documented the lessons learned.

2.4 Requirements (REQ) Working Group

The third WG, the Requirements WG, was the group tasked to lay the foundations for building an operational version of the SAVI Virtual Integration Process (VIP). The key building blocks underpinning this initial VIP capability are: (1) the Architectural Definition Language (or more properly Languages) to be used in describing the model-based, architecture centric structure of the system; (2) the Model Repository and Data Exchange Layer (MR/DEL) that supports and facilitates the interests of every user at every hierarchical layer in the system decomposition defined in parallel with a configuration management (CM) approach that takes advantage of

SAVI's model-based structure; and (3) a set of use case priorities designed to bring the most important aspects of system development to fruition in a logical sequence.

The Requirements WG consisted of Boeing (John Chilenski, Chairman), Airbus (Laurent Duffau), Boeing (Michael Kerstetter), DoD (Bruce Lewis), EMBRAER (Rodrigo Starr), Goodrich (Bernie Dion), Honeywell (Jeff Hanson), NASA (Kurt Woodham), and Rockwell Collins (Greg Pollari and Kirschen Seah). This team worked as a single team and assigned the three primary tasks to individual members as lead developers, with the rest of the WG providing advice and consent. Jeff Hanson and Kirschen Seah accepted responsibility for developing and drafting the multi-language requirements document. John Chilenski and Peter Feiler (under contract with the U. S. Army and acting for the DoD) led the development of requirements for the model repository, data exchange layer, and configuration management of these essential and data-intensive elements of the SAVI Virtual Integration Process. Finally, the prioritization of Use Cases was led by different members of the WG at various stages during this period of performance. Michael Kerstetter began collecting the information and led the initial efforts of the system integrator participants (Airbus, Boeing, and EMBRAER). Greg Pollari led the effort to draw together the inputs from the supplier community (Goodrich, Honeywell, and Rockwell Collins). Kurt Woodham led the group of government actors (DoD, FAA, and NASA) by collecting inputs from each of these stakeholders. Kurt Woodham and Greg Pollari also collected, collated, and analyzed these inputs and framed conclusions and recommendations about how to utilize the prioritization document that was produced [7].

2.5 Return on Investment (RoI) Working Group

The fourth WG, the Return on Investment (RoI) WG, was the group tasked with further enhancing the SAVI team's prediction of value for the SAVI VIP, considering an application to a large commercial aircraft as the complex system of primary interest. The members of this WG included Boeing (Steve Helton and Michael Kerstetter), DoD (Bruce Lewis), and Rockwell Collins (Greg Pollari). Specifically, during AFE 59S1, this group was tasked with adding the capability to predict hardware effects on RoI, as opposed to simply assuming that software drives the system development cost (and, therefore, the RoI) and that hardware effects can be treated adequately as a simple multiplier of software costs. Each of these projects emphasizes a different aspect of virtual integration, but both are important developments in their own right and are being pursued. The first project was conceived to specifically exercise a new project within a supplier's house.

EPoC Shadow Project Demonstration Results

Part of the Implementation Working Group's focus was on executing "shadow projects" where the SAVI VIP (Virtual Integration Process) can be applied to actual developments. The two shadow projects undertaken during AFE59S1 complement earlier SAVI AFE 59 and AFE 58 efforts by exploring applications of the SAVI VIP in two different development efforts: (1) the Aircraft Monitoring System (AMS) started as a single monitoring subsystem development (a Drivetrain Vibration Monitoring subsystem) and evolved into a multiple subsystem monitoring subsystem; and (2) the CH-47 CAAS (Common Avionics Architecture System) Upgrade which is a major system modification to an operational United States Army helicopter.

3.1 AMS Results

The original intent of this shadow project was to apply the SAVI virtual integration techniques to an actual drivetrain vibration monitoring system (DVMS) development program at Goodrich Sensors and Integrated Systems (SIS) Division. The virtual integration for this shadow project involved modeling a notional aircraft drivetrain, a vibration sensing suite, and a vibration monitoring control unit. Analyses were defined and executed, in the virtual integration environment, to verify the effectiveness of the vibration sensing suite and monitoring control unit in identifying the potential failures.

The goal of this project was to identify, using virtual integration techniques, inadequacies of a drivetrain monitoring system design before actual hardware was built. Consequently, any deficiencies in the monitoring system design would be identified, corrected, and verified before hardware is built. Another goal was to identify the benefits and savings realized in developing the vibration monitoring system using SAVI in the shadow project when compared to the standard, non-SAVI, development.

As SAVI member companies became involved with this shadow program, it became evident that this project would become a framework suitable to demonstrate the interactions among several international companies working to execute the SAVI methodology in the development of a simulated aircraft. The scope of the program was expanded beyond a simple vibration monitoring system to include a door monitoring system (Airbus), flight control systems (Embraer), engines (Honeywell), and cockpit display system (Rockwell Collins). For example, Airbus proposed the addition of a Door Monitoring System (DMS) to the shadow program. Here, the scope is expanded such that the SAVI methodology could be applied to the exploration and optimization of an architecture for a system that manages the interactions between humans and aircraft doors during different flight phases and in degraded situations.

This project's outputs, at a high level, were:

- A model repository infrastructure based on a common version control tool, SVN.
- AADL models of a drivetrain monitoring system, door monitoring system, a flight control system, engines, and a cockpit display system
- New use cases describing situations that the team identified throughout the project
- A SCADE tool/AADL translation or bridge mechanism

Hence, the goal of this project evolved into a demonstration of managing the complexity of integrating various systems into one aircraft platform by various international companies. The mechanics of cooperation in standing up the repository infrastructure and defining the virtual integration model framework became the focus of the member companies. Of special interest were the mechanisms developed to insure firewalls separating public model data from a supplier's private, proprietary data. Existing SAVI use cases were exercised where applicable, and new use cases were developed based on issues that arose during this shadow project.

Unfortunately, not all of the goals of the original AMS shadow were satisfied during the AFE 59S1. The increased scope of the project reflected the real world product and development complexities that SAVI is attempting to manage. As such, the team spent considerable time investigating and solving issues associated with setting up an infrastructure that supported international company interaction and cooperation. To this end, the deliverables from this program serve as a demonstration of feasibility of the SAVI modeling approach in a real world application. Most unfortunate was that the results of this program were not sufficient to the point where the benefits of the AMS shadow program when compared to the actual development program could be discerned.

3.1.1. Model Repository Structure for the AMS.

One of the most important outputs listed above was an SVN-based model repository infrastructure. This approach accomodates a multi-national development team and facilitates system integrator-supplier interactions, including the subsystems shown below (Figure 3). In Figure 3 the AADL *system* structure was selected to represent each subsystem. The team members responsible for each subsystem have been annotated on this chart.

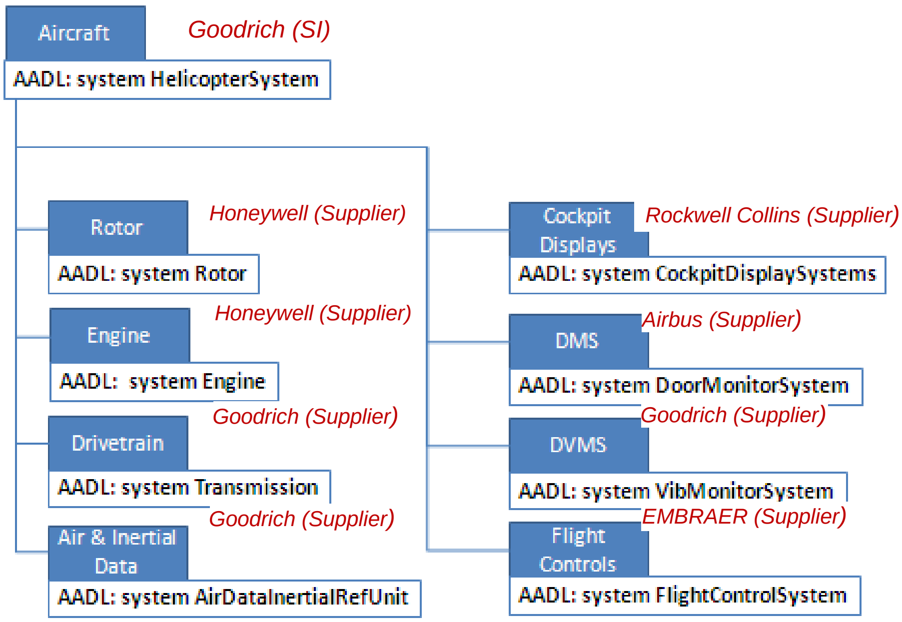


Figure 3. AADL model structure of aircraft and subsystems.

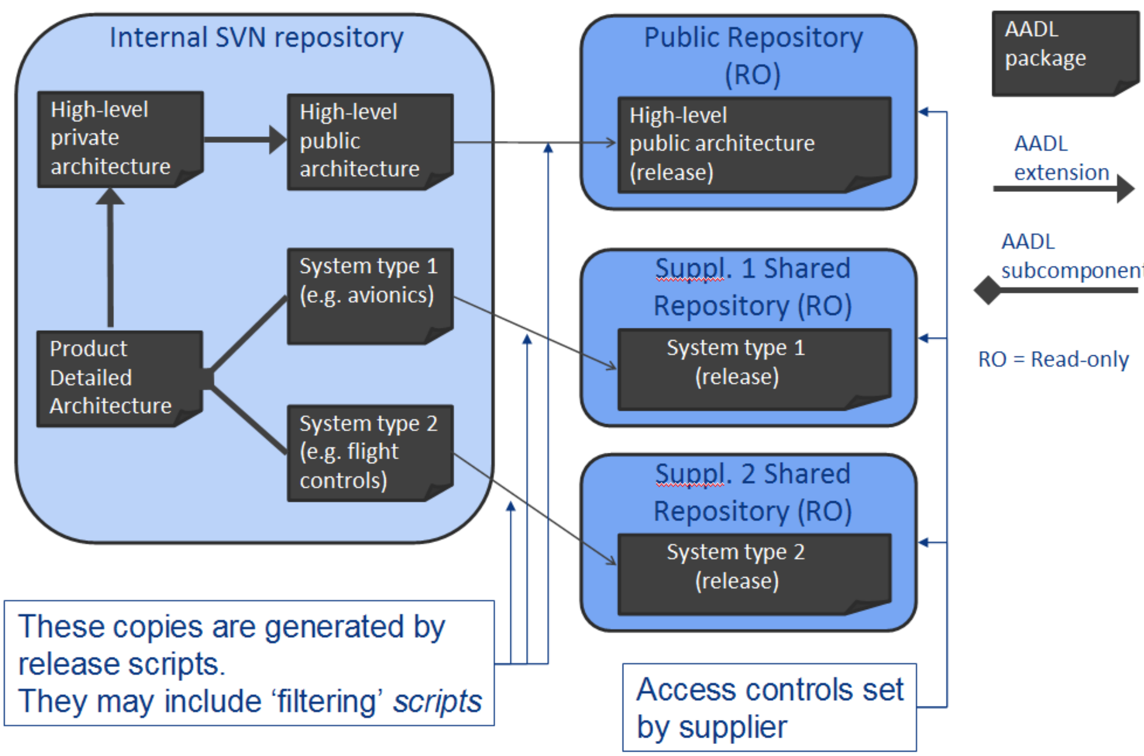


Figure 4. Private and shared repositories for an OEM (SI).

The following requirements/constraints were postulated for the AMS repository structure shown in Figures 4 and 5:

1. Each company may have a different shared interface with each of the other companies (or customer, authorities etc.);
2. Any party may choose to pass only a simplified model to the other party (OEM-supplier, supplier-supplier, supplier-OEM, etc.);
3. Each party has its own configuration management policy and cycle;
4. The configuration management policy should not be fixed for a given party. It is considered that this activity may change with every program;
5. The update of a model shared with another party must be a formal procedure, under configuration management (akin to a software release);
6. The ownership of information must be clear, in two senses:
    a. The owner of the IP must be always defined;
    b. The company allowed (and responsible) for changes must be always well defined.

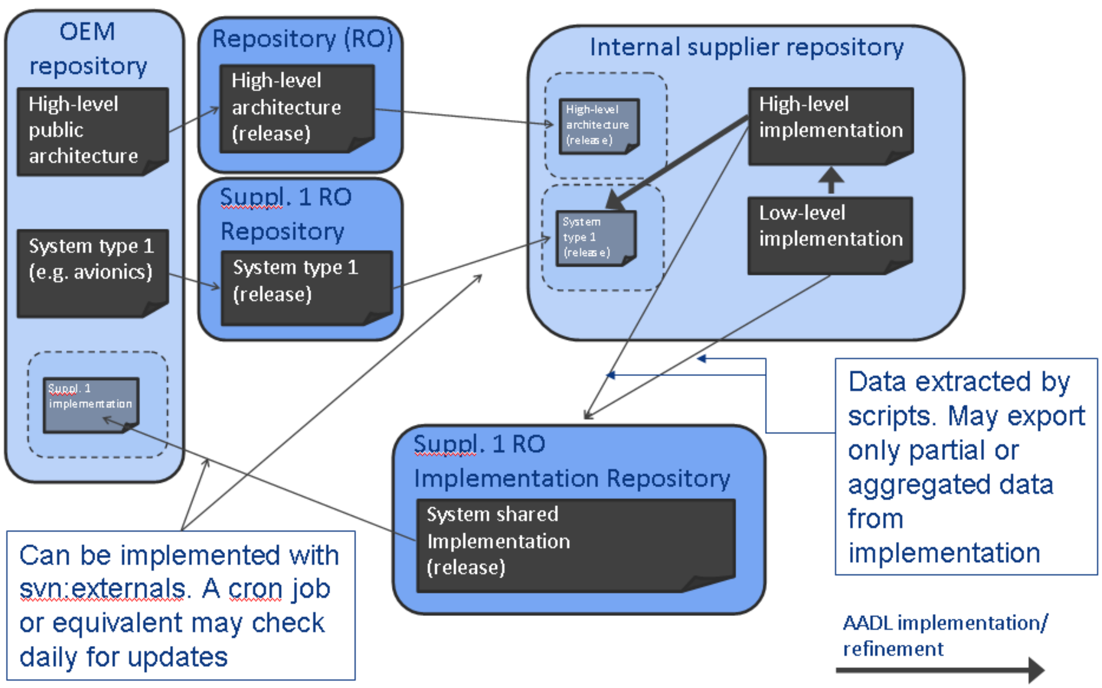


Figure 5. Private and shared repositories for a supplier.

Each company had an internal Subversion repository, where the integral system architecture was stored using AADL. This architecture was structured in different AADL packages, split into a set of OSATE projects.

The action of "exporting" a part of the architecture to shared repositories with a "filtered" copy from the internal repository to the external repository. There are two reasons for doing this filtering (instead of simply having a direct link to the internal repository):

1. Some system models may have proprietary information intermixed with information that is to be shared. Specialized scripts can clean up the information before presenting a "protected" copy. Alternatively the architecture that is provided to a supplier depends on information aggregated from the rest of the system. In this case, this aggregate value must be calculated and left explicit in the exported model.

2. "Filtered exporting" also decoupled configuration control inside a company from configuration control of interfaces with other companies. This technique allows an internal repository to hold unfinished work, while the interfaces that are seen by other stakeholders should remain consistent. The approach also facilitates change impact analysis.

Another feature that had to be settled for this repository structure was how to do model updating, a common development exercise during the virtual integration process. The process used in the AMS shadow project work is shown in Figure 6.

All of these procedures underpin protection of proprietary data, but the Data Exchange Layer (DEL) exposes model data to all parties of a development program. So, it is important to provide a robust mechanism of controlling exposure of proprietary data. The AMS shadow project exercised a prototype scheme for implementing such a protection scheme with the Model Repository structure just described.

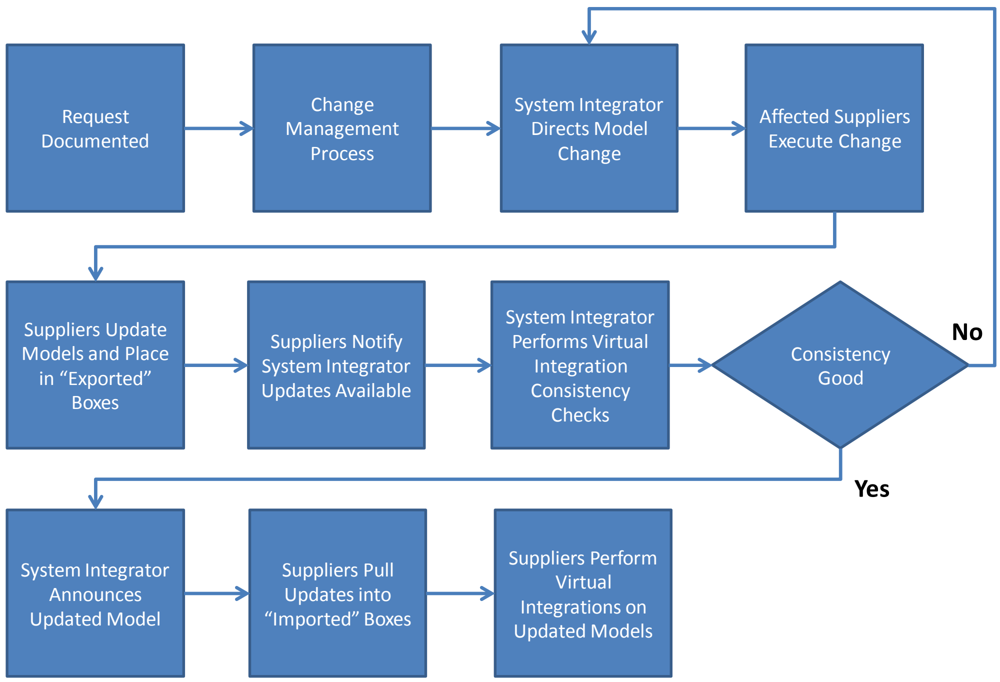


Figure 6. A process for model updates.

3.1.2. Data Exchange Layer (DEL) for the AMS.

A common version control software, SVN, in conjunction with the Eclipse IDE of AADL, was used as the protection foundation for the Data Exchange Layer mechanism used by the AMS Working Group. This software facilitated the ability of companies to protect proprietary data, while simultaneously providing access to public data over the Internet.

To avoid problems setting up the firewalls and repositories inside each company, all the repositories were created in the Texas Engineering Experiment Station (TEES) domain. Each company had a folder structure like the one shown in Figure 7. The "Internal" folder held each company's private models. The "Exported" folder held the models that have to be shared with other companies. Due to the small scale of the shadow, no means to separate which model would be seen by each company was created (and thus this was not exercised). Finally, the "Imported" folder contains only the *svn:externals* property set, and that arrangement allows the SVN to automatically pull the needed files.

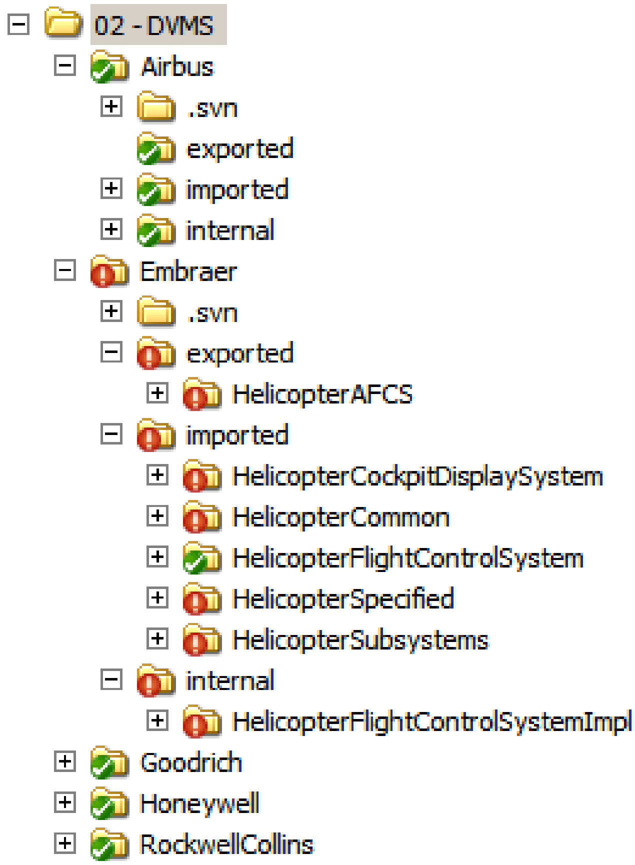


Figure 7. Folder structure used to simulate the repository structure in the AMS shadow.

3.1.3. Evaluation of the AMS Model Repository/Data Exchange Layer (MR/DEL).

The AMS Working Group exercised the prototype MR/DEL capability using a set of five use cases (see Table 2 below) to evaluate its effectiveness. Though not all five use cases were exercised, the conclusion from the evaluation was that the MR/DEL capability was sufficient to protect proprietary data while facilitating the exchange of model data among multiple, internationally based companies.

Table 2. Use cases for exercising the MR/DEL during the AMS shadow project.

Use Case Name	Purpose
Bus interconnect creation	Allow suppliers A and B to connect their systems together
Bus interconnect maintenance	Allow suppliers A and B to make additional connections to their systems, or change an existing connection
Data type creation	Allows supplier A to declare data types to be referenced by other devices; no data types have previously been made public before.
Data type documentation	Allows a supplier or integrator to generate a document based on a global data type document
Data type maintenance	Allows supplier A to change data types which are already referenced by other devices from other suppliers

3.1.4. AADL to Software Tool Integration.

This Working Group also carried out an evaluation of how to link two different software tools to the AADL architectural model. The first of these evaluations was done to link the AADL model of the Door Monitoring Subsystem (and specifically the Simplified Doors & Slides Control System or SDSCS) to the AADL Helicopter Model.

Table 3. Mapping dynamic characteristics between Modelica and AADL.

Characteristic	Modelica Representation	AADL Representation
Drivetrain Mass	Modelica.Mechanics.Translational.Components.Mass Driveshaft_M (stateSelect = StateSelect.default, m = 403.0);	HELO::DriveShaft_M => 403.0;
Bearing 1 Stiffness	Modelica.Mechanics.Translational.Components.Spring Bearing_K1 (s_rel0 = 0, c = 3200.0);	HELO::Bearing_K1 => 3200.0;
Bearing 2 Stiffness	Modelica.Mechanics.Translational.Components.Spring Bearing_K2 (s_rel0 = 0, c = 4700.0) ;	HELO::Bearing_K2 => 4700.0;

Airbus, playing the role of supplier of the Doors Monitoring Subsystem, modeled the behavior of the SDSCS and its computational element in SCADE. Since SCADE is not natively linked to the AADL model, it was desirable to link the “system” concept (from AADL) to the “node” concept (of SCADE) in a way that allows data transfer and yet maintains traceability. This latter point suggests that, when a change is made in the architectural model, impact analysis for the change can be done in the SCADE model. Standard AADL properties allow specification of where the SCADE model is stored and how inputs are mapped between the two types of models.

Though time constraints did not allow the AMS shadow project to complete a full evaluation, Goodrich laid out a scheme for mapping dynamic characteristics (mass and stiffness, for example) between Modelica and AADL. Table 3 summarizes this scheme.

3.2 CH-47 CAAS Upgrade

The U.S. Army wanted to apply the SAVI VIP to an actual project. An AADL “All in the Family” model for the CAAS architecture, developed by Rockwell Collins and maintained for the Army by Peter Feiler, already exists. The original shadow project plan sought to have the Army approve this model and associated documentation for public release so that the data would be suitable for export outside the U.S. (and thus to all SAVI members). Then, any SAVI member could participate in the shadow project and subsequent model development. However, the Army was not able to approve this existing model and documentation for publication, so the CH-47 shadow team developed an alternate execution plan. The Rockwell Collins SAVI team developed the models and provided it to Peter Feiler, who created a generic version for public release.

To compound the challenges, staffing and resource constraints for the Rockwell Collins CAAS engineering organization limited the amount of effort they could devote to learning about SAVI, learning AADL, developing the SAVI architecture model and applying the Application Specific I/O Integration Support Tool (ASIIST) analysis tool. Thus the bulk of the work for the shadow project was performed by the Rockwell Collins SAVI team members.

Since many SAVI member companies have adopted the OMG (Object Management Group) SysML architecture modeling language [8], the CH-47 CAAS Upgrade shadow project incorporates a SysML model into the SAVI VIP. The DARPA-funded META SysML-AADL translator [9] maintains two-way synchronization between the SysML and AADL models. Enhancements to the publicly available META translator [10] were provided to SAVI members.

Funding was originally intended to come from the Army, SAVI and Rockwell Collins sources, however, Army funding was not used and the effort was funded only by SAVI and Rockwell Collins.

3.2.1. Generic System Model.

Because release of the Army model was not obtained, a generic, representative model was created by Dr. Peter Feiler from SEI (similar to the one in Reference 20). This model gave the team a representative architectural model from which several different system-level analyses were demonstrated.

3.2.2. SysML-AADL Translator.

The CAAS Shadow Project team identified a representative thread that included sensors, busses, processes, processors, and display components from source documents. This thread became part of the generic model described in the previous paragraph. It was captured from system descriptions (Word documents, PowerPoint graphics, and Visio drawings) as a SysML model with the structure and constraints necessary for export to AADL using the META translator. This export step was followed by a corresponding export of the AADL model back to SysML to illustrate a “round trip” capability. This significant demonstration is essential to the SAVI paradigm so that stakeholders utilizing either of these architectural definition tools can communicate. The META translator thus realizes an important supporting mechanism for the SAVI Virtual Integration Process.

3.2.3. Application Specific I/O Integration Support Tool (ASIIST) Analyses.

Using the AADL models of this architectural thread, the team also demonstrated a specific class of analyses using ASIIST and support from the University of Illinois Urbana-Champaign (Dr. Lui Sha and his graduate students). ASIIST allowed the team to efficiently evaluate schedulability issues, bus delays, end-to-end flow problems, and bus utilization anomalies in the generic representative architectural thread. From the SAVI perspective, these analysis activities bolstered the SAVI VIP concept by showing specific examples of a slightly different system analysis tool that the VIP supports and promotes.

3.2.4. Key Outcomes and Findings.

- The extended META tool provides usable round-trip translation between SysML and AADL with reasonable constraints on use of the translator.
- Applying SAVI principles to a recently completed project suggests risk to the program can be avoided or mitigated with appropriate use of a relevant system-level analysis tool.

RoI Estimation

Previous work in AFE 58 analyzed the economic effects on the development of software-intensive systems for aircraft when deploying SAVI relative to existing development paradigms, conducted a return of investment (RoI) analysis, and computed the net present value (NPV).

AFE 59 made improvements to the original estimation methodology; spelled out assumptions, inputs required, and output parameters, and laid out two examples of use exercised during AFE 59. Specific activities included adding statistical modeling (for example, Monte Carlo analysis), estimating hardware costs in terms of effective SLOC, and building a tiered model to estimate supplier costs and benefits. During AFE 59, the SAVI RoI Estimation Tool (SRET) was further modified and also exercised to produce RoI estimates for suppliers participating in such a commercial aircraft development at varying levels in the system hierarchy. The sensitivity of the SRET to the assumptions listed above was also addressed during AFE 59. The percentage of errors discovered and corrected was varied and analyzed.

In AFE 59S1, the team began incremental development for an improved SRET that better fits the resource-limited development environment affecting most SAVI participating companies. In particular, this involved moving the models to an industry standard modeling tool for both hardware and software (Galorath SEER). The purpose of this report is to describe the refinements made to the previous approach and examine the effect those changes had on previous analyses on the return on investment of using SAVI versus the cost of SAVI development.

4.1 Targeted Improvements for AFE 59S1

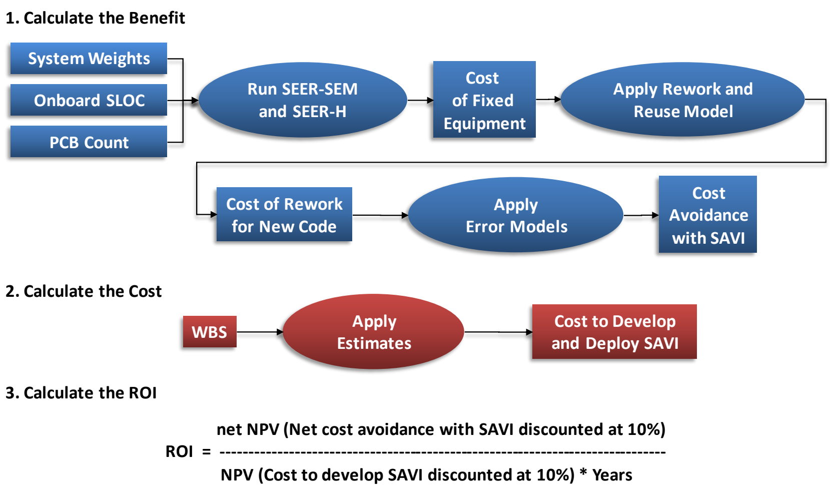


Figure 8. Return on investment computation flow.

The models used in AFE 58 and 59 did not account for weight of the airplane systems and a good way to estimate the weight was not available at the time. So it was decided to apply a multiplier of 1.55 to software lines of code (SLOC) size to estimate the effect of system weight on airplane cost. A major goal of the AFE 59S1 task was to add fidelity to the SAVI RoI estimate in this area of hardware estimation. Figure 8 illustrates the computational flow for this updated approach.

The primary assumption of the AFE 59S1 RoI study [13] was that the cost of airplane programs is primarily driven by source lines of code of software, the count of printed circuit boards (PCBs) for electronics, and the weight of the structure. This new approach represents a significant refinement in the RoI analysis; previous analyses used only SLOC as an input and estimated hardware systems cost purely through the 1.55 multiplier. These three factors are the basis of the Galorath SEER systems model adopted by this study and the AFE 59S1 return on investment analysis. Necessary constraints on the data used in the analysis were (1) that it be public so as to avoid disclosure of company intellectual property and (2) that it be conservative in order to maintain a defensible return on investment estimate for cooperating members.

Public data of this sort was difficult to find, the most contemporary set found was for a 1995-era aircraft of the 777-200 type. Therefore, the AFE 59S1 RoI study adopted the following approach:

- Build a SEER-H and SEER-SEM model of a 777-200 (1995) using SLOC and PCB estimates from Dörenberg [11], and weight estimates from Kundu [12] to obtain a total development cost for fixed equipment;
- Use the SEER development cost in the SRET to obtain a return on investment baseline for this 1995 airplane;
- Scale the model to match the SAVI target airplane delivered in 2021;
- Insert scaled fixed equipment cost into the SRET spreadsheet to get a RoI for the 2021 target airplane.

4.2 RoI Results for AFE 59S1

4.2.1. Comparison of Two Approaches.

The RoI report [13] provides a detailed discussion of the rationale used to choose conservative values for each analysis input for both the historical 1995 airplane baseline and the 2021 target airplane. The analysis of the 1995 airplane is an interesting "what if" calculation, and it yielded a return on investment of using SAVI over the cost of its development, with 40% rework and a 10% discount rate, of 18%. The process was repeated for the AFE 59S1 2026 target airplane to predict a return on investment of using SAVI on a new airplane program compared to the cost of developing SAVI (Figure 9). Even using the conservative COCOMO II model, the 2021 aircraft showed a 107% RoI with 40% rework and a 10% discount rate. Adding the improved approach for estimating system weights and scaling appropriately, the return on investment for the 2021 aircraft, with the same rework and discount percentages, was 139%. This improvement from 107% to 139% is primarily due to better modeling of hardware – the 1.55 multiplier to estimate hardware costs using an effective SLOC approach was too small. Therefore, the analysis shows that both an airplane manufacturer and Tier 1 and Tier 2 suppliers will recoup the cost of the developing SAVI on the first airplane on which SAVI is used.

AP Systems	HW + SW		AP Systems	SW Only			Enter the rose-green-rose color block of values in I
No Rework			No Rework				Will need to do this twice, once with rework value
$6,552,892,538	$10,812,272,688	$15,017,045,400	$5,848,715,900	$9,650,381,235	$13,403,307,271	CDF Output	SEER cost to develop this amount of new SLOC withou
						CDF Output	Labor months
With rework			With rework				
$8,584,289,225	$14,164,077,221	$19,672,329,474	$7,661,817,829	$12,641,999,418	$17,558,332,525	CDF Output	SEER cost to develop this amount of new SLOC with re
						CDF Output	Labor months
$2,031,396,687	$3,351,804,533	$4,655,284,074	$1,813,101,929	$2,991,618,183	$4,155,025,254	Aircraft Summary	Cost of rework
	78.95%					Cost Escalation	% of cost of rework due to requirements errors
$1,603,875,014	$2,646,393,773	$3,675,546,907	$1,431,521,918	$2,362,011,165	$3,280,571,062	Aircraft Summary	Cost of requirements errors rework
	15.79%					Cost Escalation	% of cost of rework due to design errors
$320,837,943	$529,382,606	$735,253,619	$286,360,560	$472,494,924	$656,242,951	Aircraft Summary	Cost of design errors rework
	94.75%					Cost Escalation	% of rework due to requirements errors and design erro
$1,924,712,957	$3,175,776,379	$4,410,800,526	$1,717,882,478	$2,834,506,089	$3,936,814,013	Aircraft Summary	Cost of rework due to requirements and design errors
	10%					Benefit NPV	Discount rate
33%	66%	99%				Error Model	Triangular distribution of % of requirements & design er
52.53%	66.00%	79.47%				Triang. Distr.	Expected % of errors prevented
$1,011,009,496	$2,096,012,410	$3,505,359,933	$902,365,983	$1,870,774,019	$3,128,672,453	Aircraft Summary	Cost avoidance with SAVI
$329,184,885	$682,462,040	$1,141,345,862	$293,810,536	$609,124,377	$1,018,696,347	Aircraft Benefit NPV	NPV(Cost avoidance with SAVI)
($43,007,025)	($70,961,591)	($98,557,765)	($38,385,471)	($63,336,028)	($87,966,705)	Aircraft Total Cost NPV	Cost to develop SAVI
($900,607)	($900,607)	($900,607)	($803,827)	($803,827)	($803,827)	Aircraft Deploy Cost	Cost to deploy SAVI
($30,371,893)	($50,113,624)	($69,602,255)	($27,108,117)	($44,728,392)	($62,122,767)	Aircraft Total Cost NPV	NPV(Cost to develop SAVI) of 5.5 year development
($462,154)	($462,154)	($462,154)	($412,490)	($412,490)	($412,490)	Aircraft Total Cost NPV	NPV(Cost to deploy SAVI) after 5.5 year development
108%	139%	170%	108%	139%	170%	Summary	Arithmetic Rate of Return (ROI) over 9 years from 2

Figure 9. SAVI RoI using the SEER-H cost model for a 2021 airplane and estimated incremental labor costs due to SAVI developmental stretchout.

4.2.2. Sensitivity Analyses.

A few sensitivity analyses were completed to give users of the estimation tools exposure to the added utility provided by the SEER tools. Most of the parameters checked showed either a linear variation with cost and schedule or a near-linear variation of cost and schedule with the three input parameters (SLOC, number of printed circuit boards or PCBs, and weight) assumed to dominate the cost and schedule predictions. Sensitivity analyses are valuable to check the validity of such assumptions, to facilitate trade studies, and to give insight regarding appropriate management emphasis during the development phases of the system life cycle. Figure 10 illustrates one such chart (the SEER modules offer extreme flexibility in generating tradeoff information of this type) that shows overall aircraft development cost as a function of the confidence level assumed for the cost estimate. Figure 10 illustrates a 100-iteration Monte Carlo run looking at two different assumptions about cost estimation and allowing the confidence level to vary from 10% to 90%. Notice also that for this iteration system level development costs (SLDC), the category where most of the integration effort was concentrated, were excluded. "Independent cost" means the cost outcomes of all work elements are completely unrelated to one another. On the other hand "dependent cost" indicates that the estimate was made assuming the cost of all work elements are completely correlated; that is, if one work element is estimated at a 10% confidence level, then all work elements take on that same probability. Most of the data presented in the RoI report [13] is based on the 50% (or most likely) cost estimate – the most common assumption for such estimates. However, the estimation software allows a Program Manager to consider other alternatives that take into account the most appropriate risk level for the specific development effort.

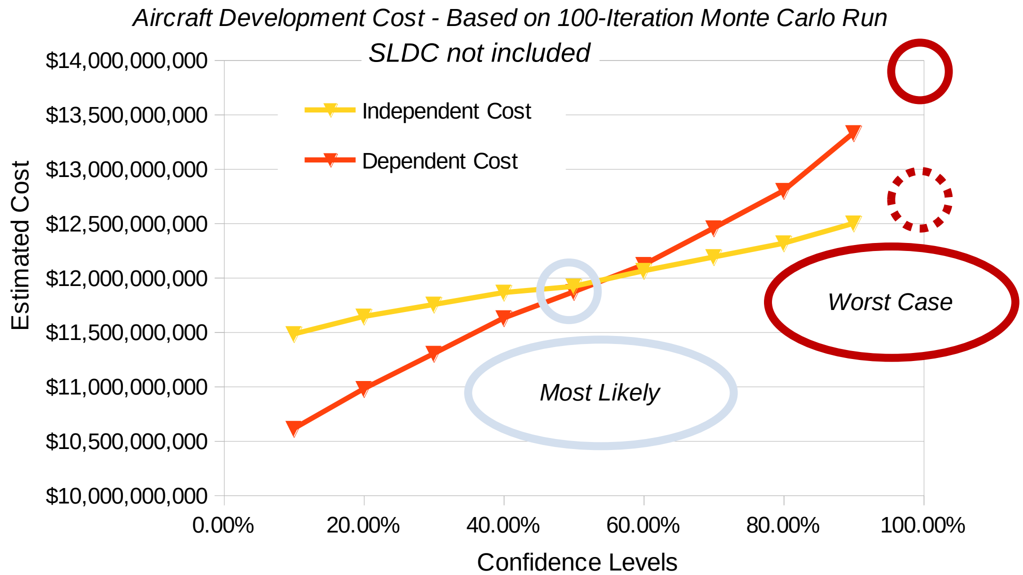


Figure 10. Aircraft development cost (excluding SLDC) estimates versus confidence level.

4.3 Summation for AFE 59S1 Cost Estimates

The difference between the approach taken in AFE 59S1 cost models and previous SAVI cost estimates is that the SEER models consistently yield a higher percentage RoI because SEER estimates a higher development cost. Ultimately, this result comes from input assumptions. SEER permits the modeler to adjust the outputs in many ways. The RoI team used settings recommended by Galorath for "number of programs" for SEER-SEM (basically 50K SLOC per program). In the end, the larger SEER-SEM exponent in the effort equation dominates, and SEER cost estimates are generally higher than SRET estimates. The SRET approach (based on COCOMO II) assumes hardware cost is directly proportional to software costs, while SEER-H has a better hardware model than a simple proportionality to effective SLOC.

The linear 1.55 hardware multiplier used in the AFE 59 RoI study is clearly not accurate. As derived from SEER-H for the 1995 aircraft example, the ratio between fixed equipment costs and system software only cost was 2.15, heavily driven by the costs associated with the weight of the systems. Furthermore, the ratio between hardware and software costs changes significantly over time. For the 2026 aircraft, the ratio is only 1.11 as SLOC explodes while weight and PCB count remain stable. System hardware only adds 10% to cost in 2021. The 1.55 ratio is accurate at some point in the time interval, but only coincidentally.

The RoI for software only was not germane to this exercise but it is interesting to note that SEER models give the same RoI for fixed equipment and for software only. There are a couple of likely reasons:

- The 1.55 multiplier in COCOMO II provides effective SLOC. This approach was simplistically used rather than calculating the correct effective SLOC to give 1.55 times the cost in the AFE59 calculations.

The multiplier becomes 1.62, slightly higher than the assumed 1.55. However, this flawed assumption is enough to make the RoIs noticeably different in the AFE59 calculations. This small difference was not recalculated for the comparisons shown previously.

- The AFE 59S1 calculation uses fixed statistical ranges, rather than the output from COCOMO II, again, likely a very small effect. The high and low percentage ranges from SRET's Monte Carlo algorithm are very close over the entire time period modeled.

It is also interesting to observe that, by 1995, airplane systems complexity had grown to the point that SAVI would have been worth doing from that time forward, although most (> 2/3) of the benefit would have been from hardware. This point is moot, however, because the distributed computing necessary to enable SAVI was not available in 1995.

Finally, the SEER modules can be easily used to evaluate sensitivities; they can facilitate trade studies; and they suggest appropriate management emphasis during system evolution.

Requirements Working Group Results

5.1 Use Case Prioritization for SAVI Version 1.0

This report provides an overview of the purpose, method of analysis, and results for the use case prioritization study conducted under Supplement 1 of SAVI AFE 59.

This analysis supports AFE 59S1 Tasks 2 and 3 by (a) extending the list of use cases developed under AFE 59 to include additional cases identified through the AFE 59S1 shadow projects, and (b) ranking the revised set as an input to the SAVI Version 1.0 requirements definition process to be conducted as part of AFE 61.

Results documented in [14] show that of the 243 AFE 59 use cases assessed, 128 were retained in the list of prioritized use cases tagged for evaluation during the four years of SAVI Version 1.0 development, with a breakdown of 77 Priority 1 (highest), 34 Priority 2, and 17 Priority 3 (lowest), using a set of prioritization scoring thresholds described in Section 2.1 of [14]. The overall number of retained use cases, as well as the relative distribution of priorities can be adjusted via a threshold table within an analysis spreadsheet that underpins the prioritization results [14].

As part of the planning process for SAVI Version 1.0, conducted at EMBRAER over the week of 14 May 2012, the SAVI PMC decided that SAVI Version 1.0A (the first year of SAVI Version 1.0 development) would primarily focus on safety analyses following processes defined in SAE ARP 4574A [15], SAE 4761 [16] and illustrated in SAE AIR 6110 [17]. Accordingly, this decision affects the use case prioritization results generated by this analysis. For example, the prioritization process generally scored individual use cases in isolation without a view towards interdependence. So, while safety-assessment use cases generally scored as high priority within this analysis, other use cases may not have been retained that generate products that are inputs to safety assessment processes. Consequently, the emphasis on safety analysis in SAVI Version 1.0A may drive selection of dependency use cases that were not retained (or anticipated) in this initial prioritization scoring.

The intent of this analysis was to provide an initial evaluation and general priorities for the span of activities that could be addressed within SAVI 1.0. As such, the prioritization was coarse, consisting only of high, medium, low, and not-retained. Per the discussion in the previous paragraph, this analysis must be harmonized with the selected focus of SAVI Version 1.0A assist in selection of new features and capabilities.

5.2 Multi-Language, Analysis, and Compatibility Considerations for SAVI Version 1.0

The System Architecture Virtual Integration (SAVI) Virtual Integration Process (VIP) is highly dependent on a "single truth" architecture model. That model needs to be defined with one (preferably) or possibly more architecture modeling languages. This section summarizes the architecture language requirements identified by the Requirements Working Group during AFE 59S1 [18].

5.2.1. General Language Considerations.

The architectural definition language (ADL) for SAVI must enable various types of consistency checking. It must be extensible, usable, and supportive of multiple views. Diagrammatic support is key, as is the ability to support analysis and reasoning about the architecture. The language must enable the ability to separate architectural concerns from design concerns and be supportive of iterative, incremental development and successive elaboration. The language should be supported by multiple tools, and have fairly mature tooling and support. It must be able to specify various types of architecture content, and should support confirming that the implemented systems conform to the definition. The paper then assesses two popular architecture definition languages, SysML and AADL against these requirements, and comes to the conclusion that AADL better satisfies the overall expectations of an architecture design language used to support the SAVI VIP.

5.2.2. Criteria for and Evaluation of AADL and SysML for the SAVI VIP.

The criteria used to evaluate these two ADLs are identified in this section. Section 2 of [18] elaborates on each of these criteria, which are loosely the set of quality attributes an Architecture Definition Language must have to effectively support SAVI Version 1.0. They include:

1. Strong semantics that enable consistency checking
2. Extensibility
3. Usability
4. Availability of multiple views
5. Diagrammatic support to aid communication and understanding
6. Analysis and reasoning support
7. Ability to separate architectural concerns from detailed design concerns
8. Multiple tool support
9. Content specification
10. Conformance to constraints for implemented systems
11. Support for iterative development/successive elaboration
12. Maturity of Language Tool Development and Support

Table 4. Requirements Working Group evaluation of AADL and SysML.

Criteria	Factor	AADL	Score	SysML	Score
Strong semantics	3	●	9	○	3
Consistency checking	3	●	9	○	3
Extensible	2	●	6	●	6
Usability	2	◘	4	◘	4
Support multiple views	1	◘	2	●	3
Diagram support	2	●	6	●	6
Analysis and reasoning support	3	●	9	◘	6
Separate architectural concerns from detailed design concerns	1	●	3	●	3
Multiple tool support	3	●	3	●	9
Content specification	3	◘	6	◘	6
Ensure implemented systems conform to constraints	1	●	3	●	3
Support iterative development	2	●	6	●	6
Maturity of tool development/support	2	◘	4	●	6
Totals			70		64

Legend: ● - Supported (3), ◘ - Partially supported (2), ○ - Not present

Based on these criteria (Table 4), the Requirements Working Group concluded that AADL is ahead of SysML as a preferred language contender, primarily for its strong semantics and ability to support consistency checking. However, AADL does have deficiencies, primarily a weakness in the specification and handling of non-electrical properties like physical geometry or mechanical properties. Due to this shortcoming, it is likely that multiple languages are needed to fully support exercising the use cases identified by the SAVI team for SAVI Version 1.0.

5.2.3. Importance of Consistency Checking.

The subgroup working on the language requirements realized very early in their work that consistency checking is fundamental to success of the SAVI VIP. With this realization they chose to include careful definitions of consistency checking that are of considerable value in not only assessing language requirements but in guiding the entire SAVI development. The types of consistency checking this team identified include:

Table 5. Types of consistency checking in the SAVI VIP.

Type of consistency checking	Description
Interface	Includes name, directional, units, semantic, range, and bit consistency across all interfaces.
Compositional	Both from dimensional and rule-based perspectives.
Constraints or assumptions	Constraints from multiple sources must be aligned.
Behavioral	Guarantees for sequencing, error propagation and handling, dynamic constraints, timing, and state/mode compatibility
Version	Addressed largely by the repository infrastructure and configuration management

Outreach Working Group Results

6.1 Outreach Activities with the Aerospace Industry

The Outreach Working Group (OUT WG - previously called the Growth, Communications, and Education Working Group [19]) was very active in pursuing opportunities to communicate SAVI principles to the aerospace industry.

6.1.1. Presentations to Various Aerospace Industry Meetings.

Table 6. SAVI presentations to aerospace industry during AFE 59S1.

Date	Conference or Presentation Title and location	Remarks/explanation
Date	**Seminar Topic**	**Presenter**
Mar. 23, 2011	*FAA REDAC – Subcommittee for Aircraft Safety Meeting, Washington, DC*	*SAVI presentation and safety video demo by Dr. Redman*
May 24-27, 2011	*IASE Conference: The Future of Commercial Aircraft, Hong Kong*	*Invited lecture by Dr. Ward*
June 14-16, 2011	*Safe & Secure Systems & Software Symposium (S5), Air Force AFRL, Dayton, OH*	*SAVI presentation and video demo by Dr. Ward*
July 20, 2011	*DARPA AVM-PI meeting, Washington, DC*	*SAVI presentation and video demo by Dr. Ward*
Sept. 13-15, 2011	*FAA 2011 National Software and Airborne Electronic Hardware Standardization Conference, St. Louis, MO*	*SAVI presentation and video demo by Dr. Ward*
Oct. 18-21,2011	*SAE 2011 AeroTech Congress &*	*AVSI/SAVI Exhibit, demos, and papers presented*

	Exhibition, Toulouse, France	*by Steve Helton, Keith Applebee, Dr. Redman*
Nov.** 9, **2011	*Global Products Data Interoperability Summit, Chandler, AZ*	*SAVI Behavior video demo and RoI paper presented by Greg Pollari and Steve Helton*
Nov. 29, 2011	*The 32st IEEE Real-Time Systems Symposium (RTSS 2011), Vienna, Austria*	*AVSI/SAVI Presentation by Dr. Redman*
Jan. 18, 2012	*OSD SE (Lead for Engineering Resilient Systems, Washington, DC*	*First briefing to OSD; Dr. Neches alone*
Mar. 21, 2012	*PDES Systems Engineering Workshop, Gaithersburg, MD*	*SAVI presentation by Dr. Ward*
Apr. 11, 2012	*OSD SE (Lead for Engineering Resilient Systems, Washington, DC*	*Second briefing to OSD; Dr. Neches; Dr. Kenyon; and Pete Lamm (AFARL); included video demo*
Apr. 19, 2012	*INCOSE North Star Chapter meeting, Golden Valley, MN*	*SAVI presentation by Dr. Redman*

The SAVI story was presented all over the world to a wide variety of audiences in the aerospace industry, varying from a single individual to international conferences. The overall goal of all these presentations was to broadly communicate with industry members and draw attention the SAVI principles, with secondary goals of reaching specific audiences with detailed descriptions of the unique features of the SAVI architecture-centric approach to virtual integration. Table 6 lists a representative set of these activities.

6.1.2. SAVI Seminar Presentations.

Early in this phase of the SAVI effort the OUT WG also decided to host and facilitate periodic one-hour seminars to be given by invited lecturers on topics of interest and germane to the SAVI development. Table 7 lays out the seminar topics and dates. Selected seminars of special interest to SAVI members were recorded and made available on the SAVI Sharepoint web site.

Table 7. SAVI seminars hosted during AFE 59S1.

Date	Seminar Topic	Presenter
Apr. 4, 2011	*META Repository (FUSED)*	*Steve Vestal*
May 2, 2011	*AADL/SysML*	*Jerome Hugues*
June** 2, **2011	*MIWG Overview*	*Sandy Friedenthal*
June** 27, **2011	*META - Complexity Reducing Design Patterns for CPS*	*Steve Miller*
July** 25, **2011	*INCOSE/OMG MBSE Efforts*	*Scott Workinger*
Aug**. 8, **2011	*Mentor Graphics: MDD for Sys Eng*	*Darrell Teegarden*
Aug. 22,2011	*Language of Languages*	*Jamie Douglass*
Sept. 12, 2011	*ITI TranscenData: LIMM*	*Rendell Hughes*
Sep**t. 19, **2011	*Physically Asynchronous Logically Synchronous Systems (PALS)*	*Lui Sha*
Nov**. 14, **2011	*Model-Based SE with SCADE System*	*Francois-Xavier Dormoy*
*Feb**. 27, 201**2*	*Compositional Analysis of Avionics Architecture Models in AADL*	*Darren Cofer/Steve Miller - Rockwell Collins*
Mar**. 5, **2012	*JHAPL M&S*	*Jim Coolahan*
May** 21, **2012	*Polarsys*	*Gael Blondelle (Obeo) & Pierre Gaufillet (Airbus)*

6.2 Infrastructure Activities within SAVI Organizations

The OUT WG also provided enhancements to the structure used for communicating within the SAVI team. The most obvious communications link maintained throughout this phase of the project was the set of teleconferences set up by and carried out by each Working Group. By far the majority of these sessions were weekly events (they were only discontinued by mutual consent of each group's membership). Minutes were carefully recorded so that any member unable to attend could readily catch up on the gist of each meeting. This procedure was begun during AFE 59 and continued through AFE 59S1.

Another internal communication tool was the Sharepoint site itself; heavy use was made of this groupware to collect and disseminate information as it was collected and to allow each SAVI participant to review and comment upon all aspects of the research and the documentation. This infrastructure was upgraded once during the course of AFE 59S1 with minimal disruption to these internal communications activities.

The OUT WG, and specifically Dr. Redman, also upgraded the public web site for SAVI. Though the number of external hits recorded by this web site remained low, the effort was deemed necessary to help get the "SAVI brand" in front of prospective new members of the SAVI team.

Integrated Process Plan

The original SAVI roadmap generated during AFE 58 (before the global economic downturn) postulated a development time of 4 ½ years with approximately 20 partners contributing two person-years of engineering expertise each year. This level of commitment was not attained. Shortly after this initial roadmap appeared, the AVSI EB directed SAVI to pursue an incremental approach to development that reduces the resources committed by each participant by over 50% and stretches out the time for SAVI VIP development. The current overall schedule (Figure 11) illustrates this modified schedule.

7.1 SAVI Incremental Development Approach

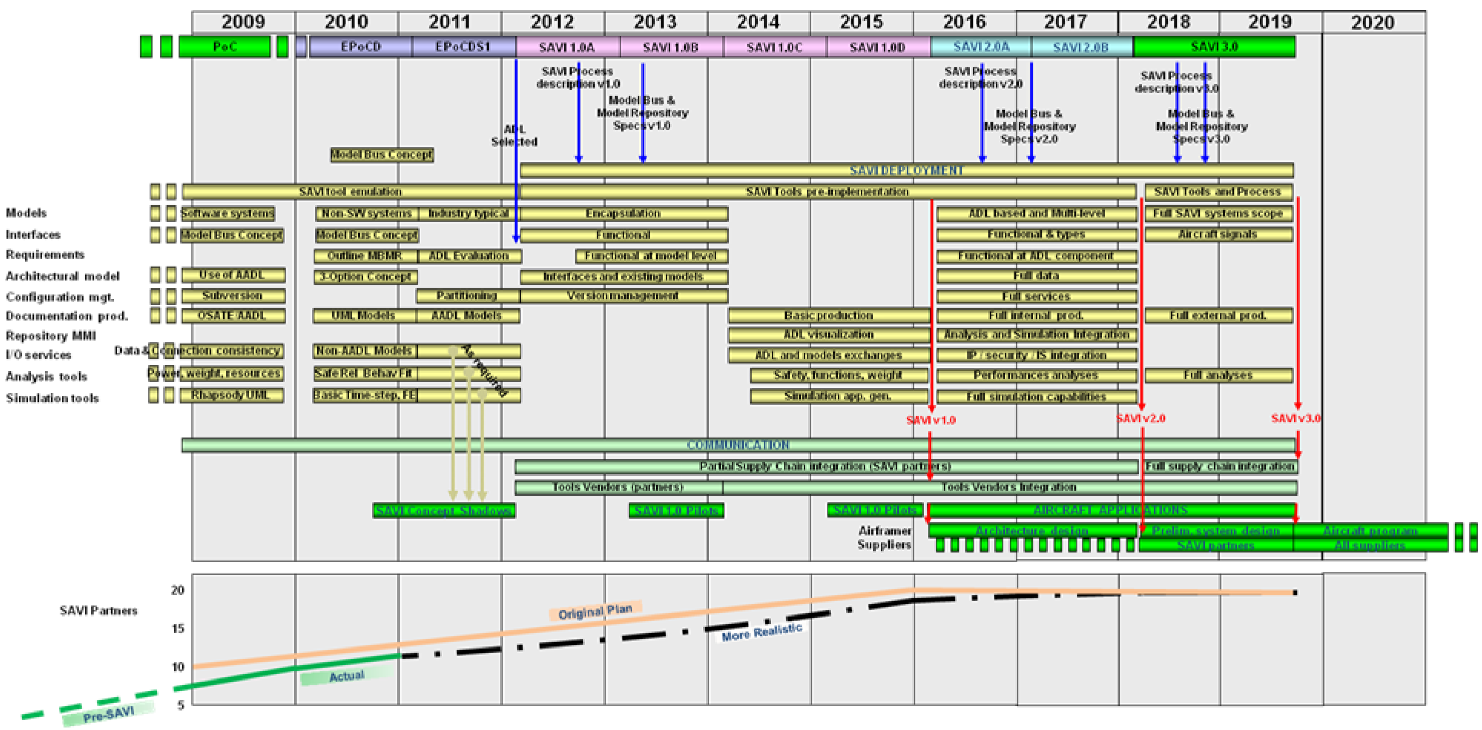


Figure 11. Revised SAVI roadmap and growth progress.

7.1.1. Proof of Concept Demonstrations.

Proof of Concept (PoC) demonstrations were carried out under AFE 58 and AFE 59 (preceding the current effort) and the results are summarized in the next section.

In the latter stages of AFE 59, it became clear that paralleling a development currently underway with a parallel development effort under the new SAVI paradigm was needed. This effort began in April 2011 and is the final stage of the PoC. This report summarizes the results of this last stage of concept demonstration for the SAVI VIP development.

7.1.2. Constraints or Bounds.

The preceding paragraphs suggest several constraints in carrying out MBSE in general or, more realistically, a critical portion of paradigm change (which the SAVI team believes is the VIP) that is needed to address the complexities faced by the aerospace industry. First and foremost are two practical issues:

- *i) obtaining the necessary human resources with the necessary skills to address modeling issues intelligently*
- *ii) securing and sustaining the management support within the entire industry (corporate, government, regulatory, and research organizations) to complete development of a paradigm shift that has acceptable risk for the stakeholders*

On a more detailed level, there are other bounds or influences to be considered:

- *iii) proprietary rights must be thoughtfully addressed and resolved in a cooperative environment (OEM, supplier, and regulator all have stakes in this part of the VIP)*
- *iv) consistency checking must be introduced at the system level and iteratively applied as the system evolves*
- *v) no single architectural description language is perfectly suited to provide all characteristics needed in a reliable VIP, which suggests strongly that multiple languages should be used*
- *vi) legacy analysis tools must be respected during the paradigm shift; the VIP must not ignore or abrogate the use of discipline-specific analysis tools; rather, the goal must be to harness the necessary results for use in the architectural analysis tools*
- *vii) the VIP developers must thoughtfully anticipate use of the system-oriented results that architectural models produce beyond the integration process that is the SAVI focus*

7.2 Current Capability and Immediate Tasks

7.2.1. Capabilities Demonstrated.

AFE 58, the first phase of the PoC demonstrations, provided strong evidence that the SAVI concept is feasible to implement. AFE 58 built and exercised an integrated multi-tiered model to demonstrate that the core concepts of analytical modeling of the integrated hardware/software/system architecture, a Model Repository (or Repositories), and the Model Bus are viable and provide promising avenues for carrying out a level of virtual integration that promises significantly lower rework costs and shorter development times for software-intensive systems. Three different sub-teams addressed the following tasks:

- *i) Definition of acquisition models – “As-Is” and “To-Be” – with emphasis on the differences between them,*
- *ii) Demonstration of a unified, incrementally elaborated, interactively analyzed architectural model, operating at three different tiers (hierarchical levels) of system development,*
- *iii) Laying out a roadmap for future development of the SAVI concept.*
- *iv) The results of these three activities, along with an industry-directed, contractor-supported evaluation of the return on investment (RoI) for SAVI-induced changes in the development*

approach for complex aerospace hardware/software systems, lead to the following conclusions:

- *The demonstrations carried out during AFE 58 strongly suggest that an analytical architectural virtual integration utilizing a common Model Bus (later called the Data Exchange Layer) with associated Model Repositories is not only feasible, but highly desirable for future systems development.*
- *With a focused and collaborative effort supported by both industry and governmental agencies a production-ready SAVI methodology can be achieved by 2014.*
- *The RoI for a mature SAVI process should definitely be positive with a highly conservative estimate at over 2% per year (most likely estimate exceeds 20% per year) on the first full aircraft development that uses SAVI techniques.*

The second phase of the PoC effort concentrated on four groups of use cases designed to demonstrate new features not addressed during AFE 58's initial phase. These use cases are just the beginnings for a large number of such structured demonstrations that SAVI must examine and illustrate capability to handle before the VIP is mature enough to facilitate integration of a complete system like a commercial or military aircraft. Specifically, these use cases addressed:

i) *integrating spatial, location, thermal, and other physical parameters into the architectural model ('fit' issues);*

ii) *assessing reliability predictions in the architectural model;*

iii) *including artifacts for system safety analysis into the architectural model; and*

iv) *demonstrating the ability to tie together descriptive behaviors (both static and dynamic) of electromechanical and structural components of a design.*

v) *Results from each of these use case sets are summarized in this list:*

- *The demonstrations were carried out successfully, lending further credence to the AFE 58 conclusion that a SAVI VIP is both feasible and desirable.*
- *The "Fit" use case demonstration showed that geometry and physical descriptions can be passed back and forth with relative ease between physical layout tools and analysis tools by taking advantage of the extensibility of AADL with straightforward scripts.*
- *Reliability use cases demonstrated software tools that facilitated passing reliability information to and from the architectural model utilizing AADL and specifically its Error Annex.*
- *Safety use cases exercised many of the same features and tools as the reliability use cases and successfully exercised two system safety analyses (the Functional Hazard Assessment or FHA and the Failure Modes and Effects Analysis or FMEA).*
- *Behavior use cases exercised both a structural element (modeled as a finite element model or FEM) similar to a wing that included a movable control surface powered by a generic servoelectrohydraulic valve (modeled in MATLAB/Simulink). Both time histories of the structural response to a generic force excitation and rather simple frequency domain parameters were readily passed between the analysis tools and the AADL architectural model. While not as automated as one might wish, the demonstration clearly illustrated feasibility for connecting such analysis tools.*

Summing up, each of these results indicates how the VIP drives further development of both AADL and its Annexes, translators, and domain-specific analysis tools. In every instance, the value of the integrated modeling effort appears to be great. Continued expansion of the RoI efforts of AFE 58 with a Monte Carlo algorithm and other refinements, showed that the payback for investing in SAVI remains at least as high as originally predicted. This work further reinforced the summary that introduction of SAVI should more than pay for SAVI development almost twice over on the first aircraft-level project to which it is applied.

7.2.2. Next Steps.

The next stage of SAVI development is meant to produce an operational VIP, albeit with limited technical maturity. Figure 11 gives the overview, but this section addresses the more immediate objectives in producing this first operational VIP capability by 2013. The SAVI PMC describes the next block of development as SAVI Version 1.0 and the objective for SAVI Version 1.0 is to develop a subset of capabilities identified in the SAVI Roadmap to a level such that this limited VIP could be incorporated with manageable risk in a program. This four years of development (Figure 12) is to mature and add to the Proof of Concept elements of SAVI and achieve a minimal set of capabilities useful to a Program Manager willing to accept the risk associated with using a VIP at a maturity level consistent with a TRL of 6 or less in exchange for potential gains in developmental efficiency. For specific subsystems this approach may be particularly useful, especially if the most significant elements of the VIP have been exercised adequately during the SAVI Version 1.0 development to mitigate this risk.

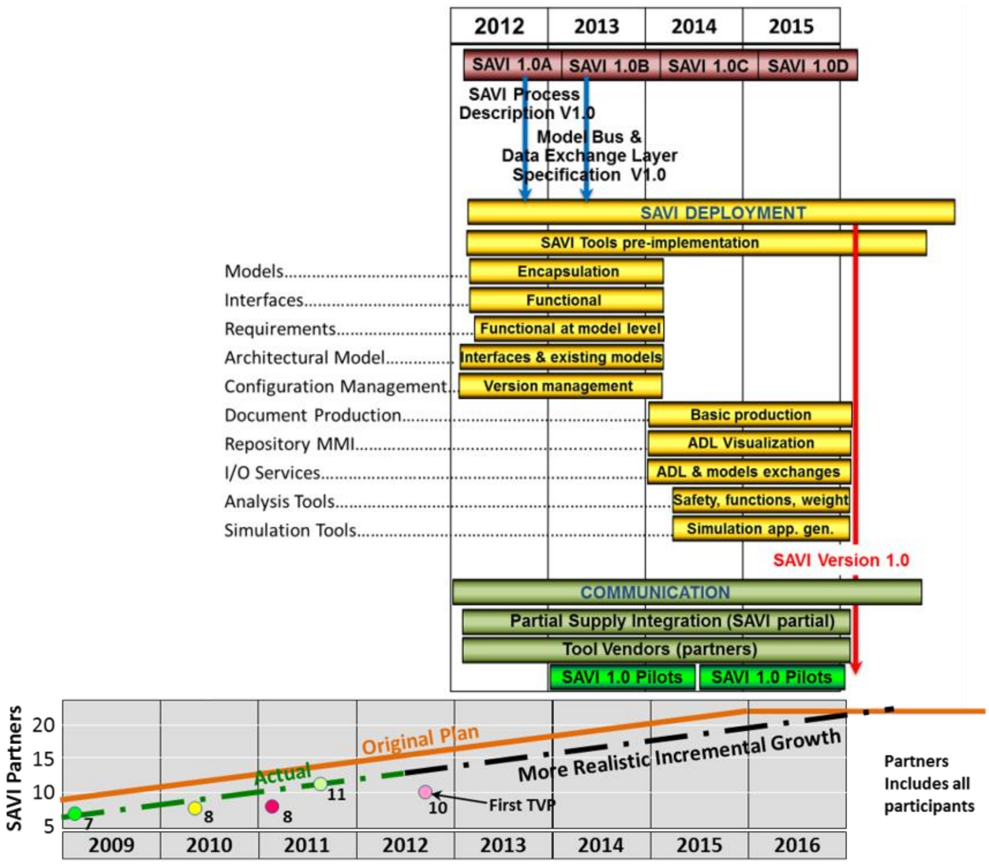


Figure 12. SAVI Version 1.0 mapped in more detail.

Figure 13 also lays out the development priorities related to the use case work done during the SAVI PoC demonstrations. At a PMC wrap-up meeting in May 2012, the SAVI team made the decision to order the four years of SAVI Version 1.0 as suggested by the numbering of the four use case groups in Figure 13. The choice was also made to concentrate first (in SAVI Version 1.0A) on system safety analysis techniques. A recent SAE publication revised system safety guidance [15], including an example stressing model-based system development [17], drove this choice. The remaining order in Figure 13 is slightly more tentative, but there was near unanimity on this first choice. Subsequent to this decision, the project plan was also expanded (Figure 14) with preliminary resource allocations [6] was laid out to support SAVI Version 1.0A development. This document [6] contains further planning details and broader vision for long-term development of the SAVI VIP, along with an appendix detailing many of the definitions and concepts that underpin SAVI.

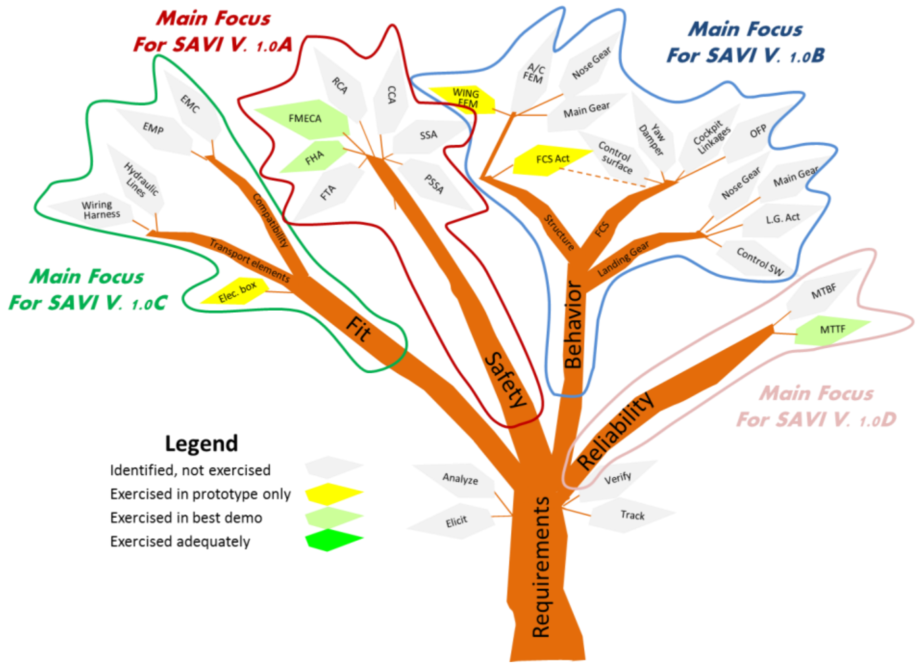
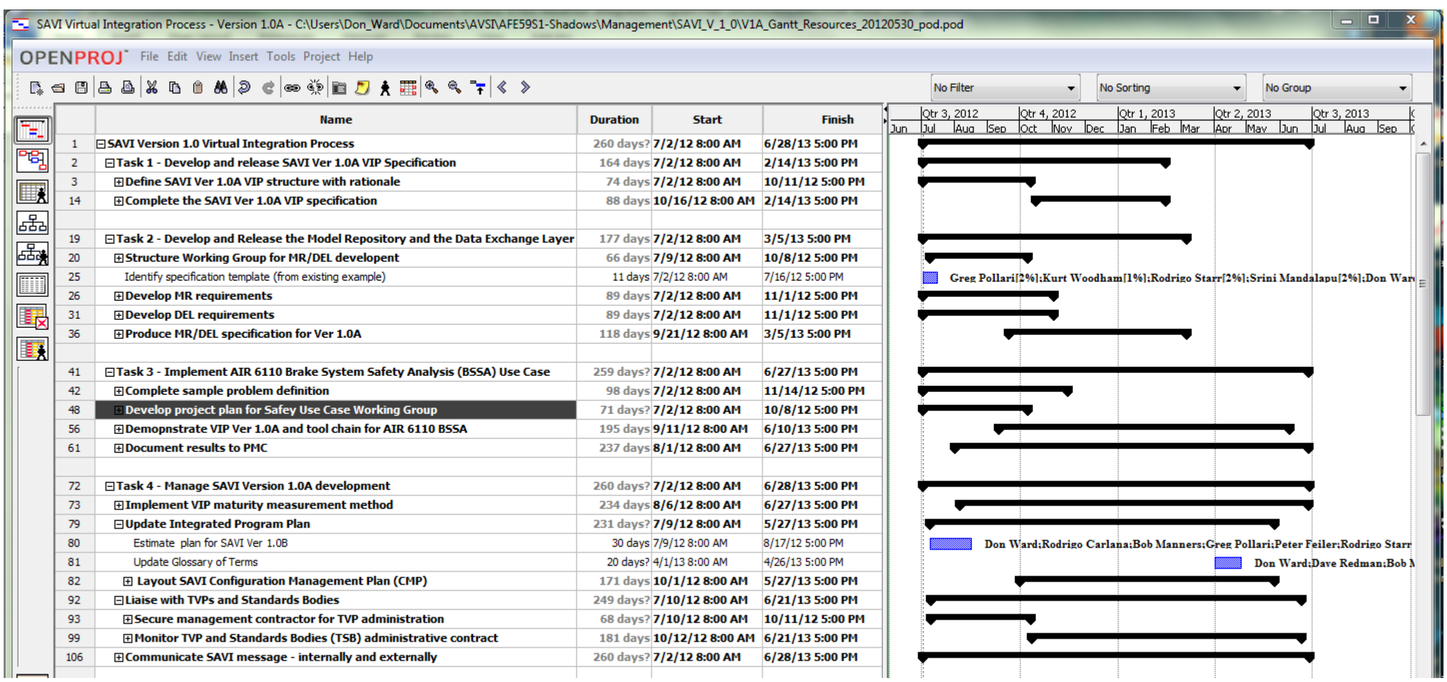


Figure 13. SAVI Version 1.0 initial capability tree.



SAVI Virtual Integration Process - Version 1.0A - C:\Users\Don_Ward\Documents\AVSI\AFE59S1-Shadows\Management\SAVI_V_1_0\V1A_Gantt_Resources_20120530_pod.pod

OPENPROJ File Edit View Insert Tools Project Help

	Name	Duration	Start	Finish
1	SAVI Version 1.0 Virtual Integration Process	260 days?	7/2/12 8:00 AM	6/28/13 5:00 PM
2	Task 1 - Develop and release SAVI Ver 1.0A VIP Specification	164 days	7/2/12 8:00 AM	2/14/13 5:00 PM
3	Define SAVI Ver 1.0A VIP structure with rationale	74 days	7/2/12 8:00 AM	10/11/12 5:00 PM
14	Complete the SAVI Ver 1.0A VIP specification	88 days	10/16/12 8:00 AM	2/14/13 5:00 PM
19	Task 2 - Develop and Release the Model Repository and the Data Exchange Layer	177 days	7/2/12 8:00 AM	3/5/13 5:00 PM
20	Structure Working Group for MR/DEL developent	66 days	7/9/12 8:00 AM	10/8/12 5:00 PM
25	Identify specification template (from existing example)	11 days	7/2/12 8:00 AM	7/16/12 5:00 PM
26	Develop MR requirements	89 days	7/2/12 8:00 AM	11/1/12 5:00 PM
31	Develop DEL requirements	89 days	7/2/12 8:00 AM	11/1/12 5:00 PM
36	Produce MR/DEL specification for Ver 1.0A	118 days	9/21/12 8:00 AM	3/5/13 5:00 PM
41	Task 3 - Implement AIR 6110 Brake System Safety Analysis (BSSA) Use Case	259 days?	7/2/12 8:00 AM	6/27/13 5:00 PM
42	Complete sample problem definition	98 days	7/2/12 8:00 AM	11/14/12 5:00 PM
48	Develop project plan for Safey Use Case Working Group	71 days?	7/2/12 8:00 AM	10/8/12 5:00 PM
56	Demopnstrate VIP Ver 1.0A and tool chain for AIR 6110 BSSA	195 days	9/11/12 8:00 AM	6/10/13 5:00 PM
61	Document results to PMC	237 days	8/1/12 8:00 AM	6/27/13 5:00 PM
72	Task 4 - Manage SAVI Version 1.0A development	260 days?	7/2/12 8:00 AM	6/28/13 5:00 PM
73	Implement VIP maturity measurement method	234 days	8/6/12 8:00 AM	6/27/13 5:00 PM
79	Update Integrated Program Plan	231 days?	7/9/12 8:00 AM	5/27/13 5:00 PM
80	Estimate plan for SAVI Ver 1.0B	30 days	7/9/12 8:00 AM	8/17/12 5:00 PM
81	Update Glossary of Terms	20 days?	4/1/13 8:00 AM	4/26/13 5:00 PM
82	Layout SAVI Configuration Management Plan (CMP)	171 days	10/1/12 8:00 AM	5/27/13 5:00 PM
92	Liaise with TVPs and Standards Bodies	249 days?	7/10/12 8:00 AM	6/21/13 5:00 PM
93	Secure management contractor for TVP administration	68 days?	7/10/12 8:00 AM	10/11/12 5:00 PM
99	Monitor TVP and Standards Bodies (TSB) administrative contract	181 days	10/12/12 8:00 AM	6/21/13 5:00 PM
106	Communicate SAVI message - internally and externally	260 days?	7/2/12 8:00 AM	6/28/13 5:00 PM

Figure 14. SAVI schedule for developing Version 1.0A safety analysis capabilities.

7.3. Options and Opportunities.

Challenges and opportunities abound for using the SAVI VIP to expand the influence and reach of MBSE. While the VIP is the heart of the matter (Figure 15), the broader context suggested by this "cloud" of interactions, illustrates the potential of MBSE to impact development of complex systems.

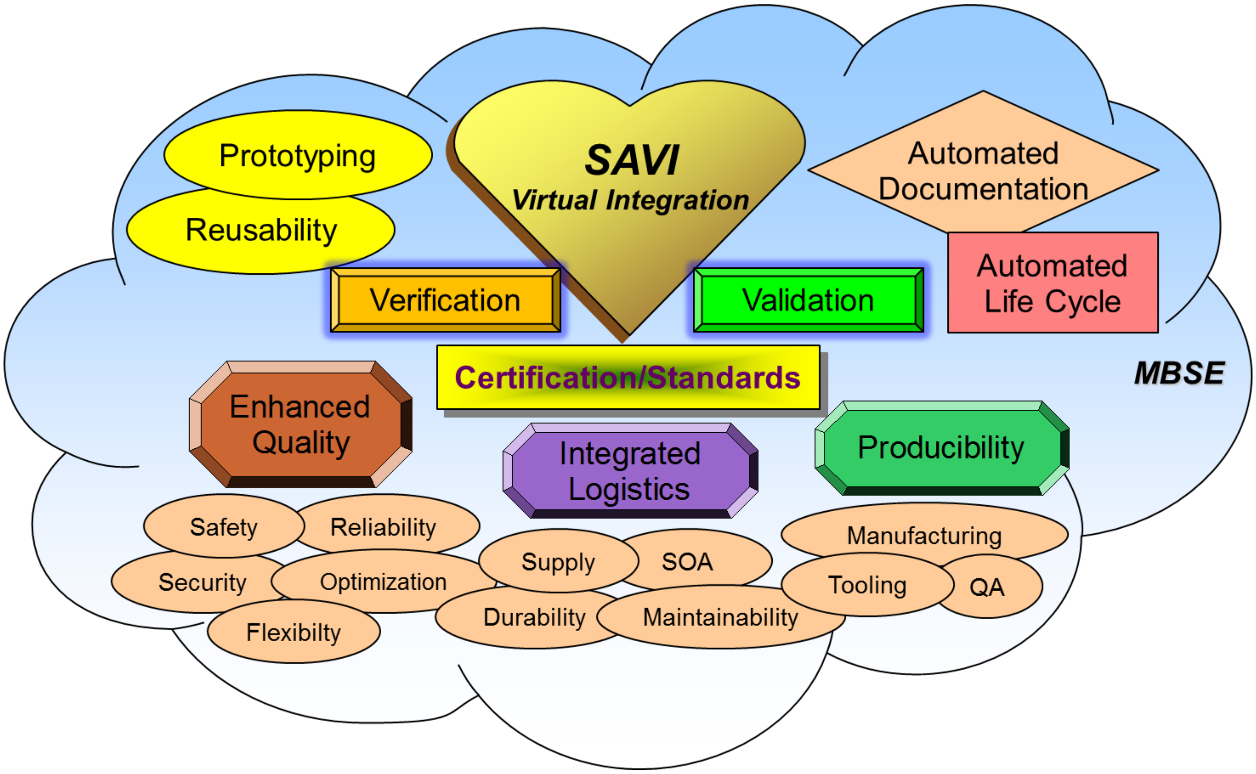


Figure 15. Heart of the benefit zone for MBSE.