Workshop Report
Air Force/LAI Workshop on
Systems Engineering for Robustness

This report contains the information generated during the June 2004 workshop with action plan and recommendations. Several action teams will transform the preliminary efforts into practical work products and guidance.

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1.0 Executive Summary

The challenges of developing and sustaining large complex engineering systems have grown significantly in the last decade. These modern day complex systems and system-of-systems require ***engineering for robustness*** to deliver engineering solutions that are:

- Capable of adapting to changes in mission and requirements;
- Expandable/scalable, and designed to accommodate growth in capability;
- Able to reliably function given changes in threats and environment;
- Effectively/affordably sustainable over their lifecycle;
- Developed using products designed for use in various platforms/systems; and
- Easily modified to leverage new technologies.

The Air Force/LAI Workshop on Systems Engineering for Robustness was held on June 8th and 9th in Arlington, Virginia. The workshop was sponsored by Dr. Marvin Sambur, Assistant Secretary of the Air Force for Acquisition and organized by the Lean Aerospace Initiative (LAI) Consortium[1]. Dr. Donna Rhodes of LAI/MIT chaired the workshop. The purpose of this event was to accelerate implementation of recent Air Force and DoD policy and initiatives for systems engineering revitalization. Participants were experienced systems engineering leaders from DoD (including the services); leading aerospace prime contractors and suppliers; NASA; commercial companies; leading universities; and industry/professional societies. A full list of participants is found in Appendix A.

Dr. Sambur gave opening remarks, and he discussed the fact that the Air Force is placing emphasis on systems engineering to address some significant problems. He remarked that there was recognition that DoD wasn't doing well in acquisition of programs, and that the average program is 36% overrun according to recent studies which disrupts the overall portfolio of programs. The primary reason cited in studies of problem programs state the number one reason for programs going off track is systems engineering. Requirements changes are not effectively handled. And we need to treat change as a reality – and project into the future of how requirements may change (a major challenge). We need to find ways to design systems so that they can easily and affordably adapt if mission or requirements change. He noted that scalability is also an issue. A significant challenge we face is being able to determine what good systems engineering is, and the Air Force is looking for a way to truly tell whether good systems engineering is being performed. A more real-time and closer look to the program is needed than can be provided by the CMMI or other models. Managing program risk means that we need an effective way to determine when and where changes in SE practice are needed on a given program. Dr. Sambur also challenged workshop attendees to think about three specific questions: (1) How do we show the value of Systems Engineering?; (2) How do you know if a program is doing good systems engineering?; and (3) What is the spiral capable development process that delivers a robust system?

Invited speaker Dr. Daniel Hastings of MIT, highlighted challenges, needs, and future directions related to developing robust systems. Invited speaker Dr. Robert Shishko of NASA/JPL, discussed the real options approach as an emerging methodology for systems engineering. Several several stage-setting presentations were given by Marty Evans (SAF ACE), Mark Wilson (AF Center for SE), Donna Rhodes (LAI), Dwight Holland (Human Factors Associates), and Bob Skalamera, OSD AT&L.

Participants engaged in one of five focus groups for the majority of the workshop. The five focus groups were: (1) Architecting for Robustness; (2) Systems Development for Robustness; (3) Robustness & Sustainment; (4) Organizational Factors & Incentives; and (5) Emerging Methodologies. Focus groups were chaired by Dr. Rashmi Jain, Stevens Institute of Technology; Dr. Dwight Holland, Human Factors Associates; Dr. Annalisa Weigel, MIT; Dr. Eric Rebentisch, LAI/MIT; and Dr. Hugh McManus, LAI/MIT. The focus group chairs were assisted by MIT graduate students Ryan Boas, Ryan Whitaker, Matt Richards, Victor Tang, and Adam Ross. The event concluded with a report of key findings of the focus group sessions, which have been incorporated into this report. Briefings for the workshop presentations are posted on the LAI website (http://www.lean.mit.edu).

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[1] LAI (Lean Aerospace Initiative) Consortium is a unique organizational entity that brings together senior level leadership from industry and government, experienced practitioners, and leading university researchers in a neutral forum. Systems Engineering is one of several current focus areas.

At the start of the workshop, Dr. Sambur posed three questions to the workshop participants as shown in the table below. Responding fully and most effectively to these questions requires longer term study and development of new knowledge, methods, and tools. However, immediate action can be taken to make significant progress by 2004 year end. Specific initiatives have been defined, as summarized in the table and described on the referenced pages of the report. The detailed descriptions are supported by the perspectives given by systems engineering experts participating in the workshop event. Action teams have been formed to work these initiatives and develop specific deliverables for use by sponsors, participants, and wider systems community. Longer term initiatives and additional recommendations are detailed on the referenced pages.

Dr. Sambur's Challenge	Six SE Initiatives	Refer to	2004 Deliverable	2004 Date
How do we show the value of Systems Engineering?	Value of Systems Engineering -- Past Study Results & Recommendations for Future Study	Page 7	***Report on Value of SE Studies and Recommendations for Government Sponsored Study***	Sep 15
How do you know if a program is doing good systems engineering?	Leading Indicators for Evaluating the Goodness of Systems Engineering on a Program	Page 8	***Recommendations for Leading Indicators for Systems Engineering***	Oct 30
	Criteria for Evaluating the Goodness of Systems Engineering on a Program	Page 9	***Key Questions Systems Leaders Need to Ask, Version 1.0***	Dec 15
What is the spiral capable development process for developing a robust system?	Guidelines for Spiral Capable Process	Page10	***Guidelines for Spiral Capable Development, Version 1.0***	Dec 15
	Considerations for Architecting Robust Systems	Page 11	***Report on Considerations for Architecting Robust Systems***	Nov 15
	Considerations for System-of-Systems/ Enterprise Engineering Concept Development	Page 12	***Report on Considerations for System-of-Systems/Enterprise Concept Development***	Nov 15

Summary of 2004 Initiatives and Deliverables. *This table shows the 2004 deliverables only. Additional initiatives and research for 2005 and beyond are recommended in the report.*

About the Report. This report describes the needs and challenges for developing robust systems and details the six initiatives, with supporting perspectives of workshop participants (listed in Appendix A). Appendix B contains the preliminary ideas on "key questions". Appendix C includes additional recommendations and perspectives of the workshop participants to be used by the action teams and in shaping additional longer term actions and research. Appendix D includes important information generated in the workshop to further shape a systems research agenda. In Appendix E, the workshop findings relevant to LAI's current initiative on a "value-based SE framework" are noted.

We encourage the use of the report summary and findings in improving systems engineering processes and practices in government, industry, and academia. We also hope the report will be a catalyst for new research projects and case studies. We request that this report be referenced as a source when used so that any follow-on impact of the workshop can be assessed. It is recognized that, while the workshop represented some of the best Systems Engineering experience and expertise from the U.S. industrial, academic and government communities, the nature of the process required the resultant recommendations and insights to be experience and anecdote based. Workshop participants, and the field of Systems Engineering, agree that important decisions, such as creation of policy, are best made in light of data-based, delineated processes and are challenged when made on the basis of experience and anecdote. Workshop participants had strong recommendations for data-based assessments supporting or challenging policy critical workshop recommendations.

Comments on the report and interest in attending any future workshops of this nature may be addressed to the workshop chair, Donna Rhodes, rhodes@mit.edu.

2.0 Needs and Challenges for Developing Robust Systems

Each focus group elaborated the needs and challenges we face in developing robust systems. These needs and challenges will be used by the various action teams to developing the deliverables.

Systems Architecting.

Robustness in system architecture can be recognized as a requirement. It should be explicitly called out with respect to identified key parameters, and modeled explicitly within the appropriate trade-space. There is a need to enumerate architectural options at a high level so that these may be effectively analyzed and evaluated for robustness of the solution. To do this we need to understand what makes an architecture robust, and this is not well understood today. We are challenged by the need to predict probabilities of change and to effectively capture the explicit assumptions we make in our architectural decisions so that these may be understood downstream in the lifecycle. We need to better understand how to involve customers in prioritizing dimensions of robustness, for example, in considering if an increase in aircraft range is a reasonable expectation. We must use domain specific knowledge for evolutionary systems, and to support this we need to collect data, models, simulations, and prototypes used in one effort to support future evolution of the system and/or future unprecedented systems. Adequate upfront systems architecting and engineering is essential to enable robustness of the solution, but this takes time and money. Further it must be accepted by DoD acquirers and contractor organizations, and protected against resource and budget cuts.

There is a need for creating a family of architectures and examining the options and tradeoff decisions, as opposed to a point design. Robustness is just one aspect of value - there are many others, all of which must be considered in a holistic manner. Further, a robust architecture must be developed against a list of "threats", scenarios, and environments rather than for a specific point design. A challenge we face is developing strategies and methods for insulating the architecture against dramatic change- for example, through layering or modularity. There is a need to separate elements that change rapidly from those that are static- adjusting for "clockspeeds." Open architectures are essential for effective component integration and evolutionary development needs to be carefully planned.

To effectively architect a highly complex system we need to be able to envision where the system will be in 20+ years, including the nature of future missions and the environment it will need to operate in. And, as systems are moving toward more collaborative SoS/FoS, we need to simultaneously define the context in which the current system will operate, as well as defining how it will play in multiple contexts over a period of time.

Systems Development

Developing robust systems means ensuring there is a reasonable ability to be adaptable and flexible over time depending upon the context/missions. As such, we need better assessment and anticipation of future states with regard to the future threat environment that the system may reasonably be expected to operate in. While systems design may need to be frozen at a given point it time, robust systems have the ability to adapt within reason to changing requirements– they must be flexible and adaptable. We need to design products with portable modularity that are relatively seamless across platforms – this is very important for military applications. There is a need to gain a better understanding of long term risks for collaborative systems in spiral development. It is very difficult to deal with concurrent projects evolved spirally and asynchronously. There is a significant challenge in balancing the need to get the product/system fielded against the need to integrate robustness.

An important factor in robust systems development is fostering a culture where people are more accepting that other real-world systems will change unilaterally. Further, it is critical that power structure in the organization should not impede information flow required to develop the system. We need to foster a joint SE-PM culture for spiral development/evolutionary acquisition. A key challenge lies in understanding what the highest value activities for systems engineering are, and in adapting processes given the unique characteristics of the program. There is a need to understand the behaviors and interfaces for interoperability of engineering processes. Better communication both internally and externally is critical, for example, with regard to reviews of system requirements for the various system disciplines.

Sustainment

During planning and development phases, effective strategies and approaches must be taken to ensure the robust solution will be supportable and affordable during the sustainment phase. There is a critical need for the sustainability specialists to get a seat at the table early on, and while involved, these specialists are not always engaged fully in the systems architecting and systems development phases. The use of COTS introduces specific challenges in sustainment – will the technology be available for the planned lifecycle of the program and how will upgrades be handled?

Incentives on programs do not typically focus on ensuring decisions are optimal for sustainability of the system in an evolutionary development program. There is a need to develop effective strategies for balancing the near term decisions with appropriate uncertainty and options for ensuring flexibility for the later growth and evolution. Funding development programs from a "stovepipe" perspective deters making lifecycle cost-benefit trades. Total ownership cost needs to be a key metric. Program managers are often incentivized to take too short term a focus; project managers don't want to pay for options beyond what is written in the specification.

Operational data on performance of military hardware needs to be provided to future systems designers. We lack metrics, data, and benchmarks for successfully addressing sustainability of systems and thus sustainment has not historically been adequately addressed as part of systems engineering. Some progress has been made, but more focus and education on this aspect of systems engineering is needed. We have an opportunity exists to better educate acquisition workforce, contractor workforce on assessment of supportability/sustainability of systems.

<u>Organizational Factors</u>

Highly complex systems and system-of-systems efforts result in very challenging dynamics regarding how decisions are made. Organizational factors are, therefore, major drivers in how robust the system solution will be. Decisions made at "local" levels are not always the right ones for the "global" level systems challenges. We face a significant challenge given that the commitment to robustness is fragmented without champions at all levels of a program. This is further complicated by the system-of-systems programs with multi-stakeholders who have specific requirements and metrics that may drive them to suboptimal decisions for overall robustness of a complex system solution.

The prevailing culture creates an environment that drives government and industry to compromise under political pressures resulting in unrealistic schedules and costs. Neither government nor industry has effective organizational structures or processes to address systems engineering robustness on highly complex endeavors. Without government incentives, the strategic context of robustness is viewed in isolation without addressing technology roadmaps, investments, manufacturing; potentially risking making robustness a tactical "flavor of the month." With insufficient SE personnel in the workforce, in the pipeline, or in training, the organizational aspects of the "robustness challenge" are sure to continue. There is a need for common terminology and methodologies across stakeholder boundaries to ensure more effective collaboration on a complex endeavor.

<u>Emerging Methods</u>

Advances in methodologies and supporting toolsets are beginning to enable robust engineering. However, these are not yet fully validated for effective use, nor are they widely understood by systems practitioners. These emerging methods tend to be used more often in new development programs although this remains a challenge due to understanding and inadequate funding/resources. And, there is a significant challenge (both organizationally and culturally) in inserting robustness methods into existing programs. The work products generated using emerging methods are internal and less visible externally. As such these are easily overlooked and there may be key systems issues that are missed until downstream. Use of these methods is compromised by budget pressures, and result in poor decisions being made regarding robustness.

We need to mature, validate, and insert the promising emerging methods and tools for engineering for robustness on systems programs. These may include methods for trade space exploration, real options, product lines, model-based X, and others. We lack enterprise-level calibrated risk models.

A particular challenge lies in funding such efforts, and there is an important need to prove (and capture learning and results) on the ROI on using these methods. The further development of and use of emerging methods is threatened if the value of these methods is not demonstrated, and this is further complicated by the lack of funding sources for such work. We need tools to support SoS aspects of development, that do what the systems tools can not. The outputs must be easy to communicate and methods must be minimally invasive to existing tool environment.

3.0 SIX SYSTEMS ENGINEERING INITIATIVES

The following six initiatives will be addressed by action teams comprised of leading systems engineering experts. The LAI POC for these initiatives is Donna Rhodes, MIT/LAI, rhodes@mit.edu. The initiatives will produce specific deliverable in 2004, and these will be made available on the LAI website.

Initiative One

Value of Systems Engineering – Past Studies & Recommendations for Future Study

Programs do not always apply the systems engineering process effectively and efficiently. Studies show that when resources are cut on complex systems programs, the systems engineering budget is one of the prime targets for such cuts. One of the underlying reasons for such decisions is that we lack the objective, quantitative data to show the value of systems engineering on a program. Further, while early studies show overall that systems engineering investment pays off, we lack knowledge about which systems engineering activities are the highest value for the investment.

2004 Action Plan	Deliverable
An action team has been formed to gather the work to date that has been done on "value of systems engineering" by INCOSE, NASA, RAND, and other organizations. This compilation of information can serve to guide additional efforts in this area. A sponsored study will be needed to gain the information desired on the value of systems engineering, and the action team will also formulate a recommendation concerning such a study.	***Report on Value of SE Studies and Recommendations for Government Sponsored Study*** • September 15, 2004

Additional Recommendations: We strongly recommended that there be a government sponsored study to collect detailed quantitative data on the value of SE (at the activity level) on several programs on a real-time basis over the program development lifecycle. This study will require funding from the government (or other source) and should be performed by a knowledgeable and neutral organization such as an FFRDC or consortium. The 2004 report will include recommendations for a study of this nature. The study should be designed to provide information which will discern what systems engineering activities are highest value given program context, and should assist acquisition leadership in RFP and contract development.

Perspectives of the Workshop Participants

What do we do well today?	What are we not doing well today?
Several studies have been undertaken on the value of systems engineering. These are based primarily on subjective data captured after the fact so they are inconclusive. The findings done to date do show positive trends and there is optimism that a formal study will yield results that clearly demonstrate the value of systems engineering to a program.	While several studies have been done, no one has stepped up to a full study and this is in part due to lack of funding as well as related to the difficulties in gaining access to the necessary data. Yet, this is very important as without objective, quantified evidence of the value-add of systems engineering on a program, we have difficulty convincing customers that money needs to be spent on front-end engineering. Softer aspects, such as the valuation of flexibility by customers, are even more difficult to discern and quantify.
What are the inhibitors or barriers?	**What are improvement opportunities?**
Our inability to quantify the value of good systems engineering in the development process inhibits the sustained commitment of resources to these activities. The issue of access to data on a real time basis is a significant one. Effective levels of access would require a trusted neutral party, with authority and clearances to view program specific information. Therefore such a study may best be undertaken by an FFRDC with systems engineering expertise, perhaps in collaboration with a university and or consortium.	There is high interest in research on the value of systems engineering. Research needs to be done by a neutral party with significant expertise. Such a study needs to be long term, collecting data real time during program execution. If such studies can be accomplished with positive results, then better justification can be made for funding systems engineering as an important component of the larger acquisition process. Further, we need to understand which SE activities provide the most value in context of program and organizational factors. The first step, already in progress, is raising the awareness of the importance of good systems engineering.

Initiative Two Leading Indicators for Evaluating Goodness of Systems Engineering on a Program	
Program leaders evaluating whether their programs are doing good systems engineering need to have access to a set of leading indicators. Today, we have many good leading indicators for the programmatic aspects of engineering, but lack good leading indicators of the more engineering aspects of a program.	
2004 Action Plan A "Leading Indicators Action Team" has been formed, comprised of experts on engineering metrics and measurement processes. Some leading indicators are included in the AF Guide on Engineering for Robustness; this team will develop and propose an expanded set of leading indicators for systems engineering. The leading indicators should be piloted and validated through several studies before broad use.	Deliverable ***Recommendations for Leading Indicators for Systems Engineering***, Version 1.0 • Oct 30, 2004
Additional Recommendations: Using the action team's recommendations, the Air Force should establish pilot programs for these leading indicators to validate and assess usefulness to leadership in government and industry. Based on results of pilot programs, the leading indictors need to be adjusted as required and recommendations developed regarding which leading indicators are most effective for particular types of programs.	
Perspectives of the Workshop Participants	
What do we do well today? We have good leading indicators for the more programmatic aspects of engineering such as cost and schedule performance. Sound technical performance measures exist for most programs and we have approaches to track and manage these. The current AF Guide on Engineering for Robustness includes some useful measures and the new leading indicators can be published in this guide.	What are we not doing well today? We do not have leading indicators for the goodness of systems engineering effort or the desired aspects of the systems being developed. For example, we have no leading indicators for robustness, flexibility, architectural integrity, etc. And, we lack systems engineering measurements that are useful and reasonably immune to distortion.
What are the inhibitors or barriers? Leading indicators for systems engineering are difficult to define. There is some perception today that there is an the intrusion of excessive metrics, and we need to avoid any new initiative being viewed in such a way. There is also a risk of galvanizing prematurely on immature metrics strategies, contract language, etc., if validation of the leading indicators is not properly done.	What are the improvement opportunities? There is a rich opportunity to define a new set of leading indicators that is targeted at SoS and complex enterprises. There is great potential for effective progress if we the various groups thinking about this subject (PSM, INCOSE, LAI, SPC, etc.) to integrate current leading indictors/metrics research and practices.

Initiative Three

Criteria for Evaluating the Goodness of Systems Engineering on a Program

Program leaders need to be able to evaluate whether their programs are doing good systems engineering – that is, whether systems engineering practices are being applied in a manner that will effectively and affordably deliver a robust system solution. The specific criteria one uses to evaluate the goodness of systems engineering is also not well understood, nor is it captured in a way which can help program leadership ask the right questions of their program teams during the engineering effort.

2004 Action Plan	Deliverable
An action team has been formed to develop the criteria for evaluating the goodness of systems engineering (criteria are formatted as questions to be asked of engineering teams). This "Key Questions Action Team" will refine the preliminary work from the workshop (see Appendix B) to create a set of specific questions systems leaders need to be asking their program teams to gather the information they need to discern whether good systems engineering is being practiced.	***Key Questions Systems Leaders Need to Ask***, Version 1.0 to be used as guidance to help systems leaders ask the right questions of their program teams • Dec 15, 2004

Additional Recommendations: The action team will make a recommendation to the LAI Consortium for an effort to development a version 2.0 of the ***Key Questions Systems Leaders Need to Ask***, which would include preferred responses to the questions in context of the program characteristics. It is critical that the action team identify a set of knowledge transfer partners (e.g., LAI, SPC, AF CSE, AF ACE, etc.) who can ensure that the developed product is effectively used on programs.

Perspectives of the Workshop Participants

What do we do well today?	What are we not doing well today?
There is a growing recognition that SE is critical to the success of a program. We have models such as CMMI that are used to determine if an organization has the processes needed to be capable of doing good engineering. There are significant levels of process definition and training in many organizations today. The SE infrastructure is strong in many organizations today, with dedicated and knowledgeable professionals. We strive to evaluate good systems engineering through program reviews.	While we have models for evaluating organizational systems engineering capability, we do not have the criteria for evaluating how well systems engineering is being applied on a specific program. When program reviews are conducted, we do not always ask the right set of questions about the application of systems engineering on the program. And, even when the questions asked are good ones, we do not always know what the 'optimal' answer is in context of a highly complex system or system-of-systems effort.
What are the inhibitors or barriers?	**What are the improvement opportunities?**
CMMI can sometimes give a false sense of security; an organization may be capable of applying good systems engineering processes but may not actually be applying the right processes and people to a given program. We have an over-reliance on captured processes rather than the ensuring problem solving and actions by people on a program. Also, we see focus on longer term systems considerations fade as short-term cost and schedule concerns arise.	Our current engineering workforce is often unable to understand and manage the increasing systems complexities (technical and management), and supportive guidance and tools are needed. The opportunity exists to create a comprehensive set of questions that need to be asked on highly complex systems project, along with characterizing the answers that we should be expecting teams to provide. We also need to do a better job of educating our systems leadership on attributes of good applied systems engineering.

Initiative Four

Guidelines for Spiral Capable Development Process

Systems engineering for robustness requires a development process that will enable the development of the system in an evolutionary manner, and will accommodate new technologies and changes in mission, requirements, and technologies over time. Today's engineering processes fall short of this, and guidelines are needed to enhance the process to be 'spiral capable'.

2004 Action Plan	Deliverable
An action team will be formed to propose a development process that is 'spiral capable'. Previous research by LAI and other organizations, as well as information developed during the workshop, will be used in the development of the guidelines.	***Guidelines for a Spiral Capable Development Process,*** Version 1.0 • Dec 15, 2004

Additional Recommendations: The government must advocate and sponsor/fund further development of the methods and supporting tools to fully realize a spiral capable process on systems/SoS programs. LAI and other research entities need to contribute through targeted research and the development of case studies of the experience of large complex programs using this approach.

Perspectives of the Workshop Participants

What do we do well today?

We have a good foundation of systems engineering to build on. We generally have good approaches to requirements management, with sound decomposition processes and good requirements to design practices so any new process needs to leverage these where possible. Similarly, today's technology is an enabler, for example, it allows for better integration and verification capabilities than were possible in the past. In defining a new process, we have many best practices that can be incorporated, for example, effectively using IPTs to develop system requirements. Preliminary work on this subject by LAI, FFRDCs, and industry that can contribute to development of a set of guidelines.

What are we not doing well today?

A 'best practice' for spiral capable development is not yet identified. We see today major gaps in what the users want and what is communicated in specifications about what the users want. We are not always using known SE processes; we are reinventing – so if a 'best practice' is identified we need to ensure it is communicated and used. Despite best intentions, too much ad hoc engineering (e.g., fielding of prototypes) may lead to less robust processes so we need to ensure that the spiral capable process address full lifecycle/full enterprise needs. Effective systems integration, lessons learned, and date of art knowledge is not fully applied in front end of programs.

What are the inhibitors or barriers?

The major barrier to a spiral capable process is the inability to adapt traditional SE process for contemporary challenges and evolutionary approach. Often today, SE management takes a primary focus in the process; we need to ensure that SE is engineering intensive to address current challenges. Accelerated development cycles can only go so far before unacceptable risks are incurred; so spirals must be effectively planned to ensure decisions happen at appropriate spirals in the overall effort. Today, we are not maintaining flexibility in the requirements long enough in the design process to properly accommodate all downstream implications and needs. Prevailing approaches use deterministic engineering thinking; they do not emphasize evolutionary thinking and robustness to significant degree. Another inhibitor is that we do not get the entire team working on a SoS effort together on a frequent enough basis; there has been insufficient dialogue on how to best approach cross-cutting requirements and complex enterprises issues as part of the spiral process. Spiral development includes harsh realities to both the supply-base and the user-community. A spiral development program with limited lot sizes may not include adequate production volume to cover the costs of capitalization, tooling, or non-recurring engineering associated with technology maturation. It will also limit the experience base required to "learn-out" the system issues and apply statistical-process-control to ensure a quality deliverable to the users.

What are the improvement opportunities?

The spiral approach offers advantages in developing robust systems. Spiral approaches can help to ensure that uncertainty is managed and addressed at appropriate increments. Validation by end users at each spiral will help deliver the system the users really want. Spiral development can permit more flexible program management contractual relationships. Defining a new process provides us with the opportunity to try to address today's shortfalls which include:

- Risk identification and risk management post-delivery is not done well.
- We are not always very good at prioritizing user needs to fit within budget.
- Technology development programs do not always investigate robustness /flexibility/scalability of overall system.
- Business/technical issues are not well integrated into the current systems engineering functions.
- SE practices/approaches are often inconsistent with the HW/SW engineering practices on a program.
- We often insufficiently perform front-end needs analysis.

Initiative Five

Considerations for Architecting Robust Systems

Systems architecting practices are evolving as more formalized and quantitative practices. The implications for developing robust solutions are significant. Further, these practices need to evolve to better accommodate evolutionary development and the challenges of SoS/FoS programs. Architecting practices must be supported by methodologies and tools to enable better trade analysis, impact assessment, and predictability. Better methods for evaluating architectures should be part of the enhanced practice. Research and case studies are needed to develop and validate enhanced architecting practices.

2004 Action Plan	Deliverable
An action team has been formed to refine the information gathered in the June workshop. This refined information will be captured in a report for use by architecting related working groups and research centers. The action team will also develop a plan for conducting a workshop on systems architecting in 2005.	***Report on Considerations for Architecting Robust Systems*** • Nov 15, 2004

Additional Recommendations: The government must advocate and sponsor/fund research on methods and supporting tools to evolve a formal systems architecting science. LAI and other research entities must develop case studies of the architecting experiences of large complex programs. It is strongly recommended that INCOSE use the report of this action team in its planned systems architect certification program.

Perspectives of the Workshop Participants

What do we do well today?	What are we not doing well today?
Systems architecting practices have been evolving to increased levels of maturity, and architecture frameworks have been introduced. An example of good current process is that when existing SE processes and structures are properly applied, our practices isolate things that change from things that don't in order to insulate against dramatic criterion through layering, modularity, partitioning. There are some existing working groups, research centers, and universities who are focused on improving the state of the art and practice of systems engineering. Systems architecting is being taught in many universities today.	Systems architecting practices are relatively young. Frameworks have emerged to capture architecture descriptions but effective evaluation approaches have not yet been defined. Further, we do not adequately identify attributes of systems architecture that would allow supporting variable requirements. We are still not very effective in predicting probability and impact of change and making explicit assumptions. There is a need for better systems architecting for manufacturability and sustainment (lifecycle considerations). We have insufficient systems architecting practices for 'Planned Evolutionary' systems. We often do not assess the multiple problems and opportunities given changing environment, new technologies, new threats, etc.
What are the inhibitors or barriers?	**What are the improvement opportunities?**
Lack of good upfront Systems Engineering, and its associated investment, inhibits the robustness of the solution. Robustness is threatened by unavailability and inadequacy of funding. Poorly defined user needs/requirements management threatens performance outcomes. The lack of multi-disciplinary (high level) perspective for systems architecting is a barrier to a robust solution. There is often a resistance to bring in people from other non-traditional disciplines. We have insufficient open architectures for integrating components between multiple vendors. Robustness is often domain and discipline specific; needs to be translated and transported across disciplines/domains for SoS. Technology readiness level is stretched in the competitive environment and there is not enough SE on the front end to prevent single-point program issues.	There are many systems experts who are focused on systems architecting practices, and bringing together the contemporary thoughts on the subject will be useful. Identifying a 'Family'/ 'Class' of architectures could provide increased opportunity to consider options and perform trade-offs. We will benefit from systems architecting for 'Class' of threats, scenarios (including future scenarios), environments and not a specific environment. There is an opportunity for improved use of domain-specific knowledge, data collection, prototyping modeling, develop concepts for bounding uncertainties. We don't know how to identify and asses multiple futures outside of the defined context.

Initiative Six Considerations for System-of-Systems/Enterprise Engineering	
System-of-systems and complex enterprise engineering presents new challenges in effectively defining, trading-off, and converging on the full enterprise stakeholder needs. While system-of-systems are often thought of as just a larger system, there are higher level operational requirements. The development of robust system-of-systems begins with a well-elaborated system vision that incorporates the perspectives and needs of the full set of enterprise stakeholders. This is critical to the success of the engineering development which will follow; building a shared vision and understanding for the enterprise will have positive impact on the ability to respond to changes in requirements, mission, and environment during later phases.	
2004 Action Plan A specific research study has been initiated at MIT/LAI in collaboration with MITRE Corporation to investigate the Air Force's airborne network as a complex adaptive system. MITRE is in the process of re-examining its traditional role, methods, skills, etc. in light of the trend toward supporting customers at the enterprise level. An executive level MITRE objective is supporting an investigation into the differences between traditional SE and that which might be needed to deal with complex adaptive systems. One or more workshops are planned to gain feedback on the proposed approach and further the thinking on the results of the MITRE/MIT study.	Deliverable ***Report on Considerations for System-of-Systems/Enterprise Engineering*** • Nov 15, 2004
Additional Recommendations: The government must advocate and sponsor/fund research on methods and supporting tools if we are to evolve the present engineering science to serve the needs of SoS/Enterprise Engineering. LAI and other research entities can contribute through research initiatives and developing case studies of the experiences of large complex programs.	

Perspectives of the Workshop Participants	
What do we do well today? There has been some research on this subject which provides foundational thinking for further study. Today we have techniques for stakeholder needs convergence and for developing scenarios, but not for the more complex systems/enterprises.	What are we not doing well today? Modern systems and the complex enterprises that develop, operate, and sustain them require approaches beyond what has traditionally been used. We do not clearly understand the challenges and strategies for SoS/FoS versus system. We don't fully account for "n" dimensionality of these types of programs and enterprises.
What are the inhibitors or barriers? We struggle with getting agreement from customers/stakeholders on what is important in a highly complex adaptive system enterprise. The organizational structure and enabling infrastructures can have a major impact to the concept development. There is a significant mind-shift required to move from 'stove-piped' to horizontal integration. We do not fully understand how to do enterprise engineering.	What are the improvement opportunities? An approach is needed to better involve all stakeholders and customers in prioritizing the dimensions of the system (and enterprise). We have not effectively adapted SE processes to address the SoS/complex enterprise challenges; new approaches are needed.

Appendix A. List of Workshop Participants

Mr. Danny Abbott, Air Force/ACE
Mr. William Albery, AFRL/HEPG
Dr. Elliot Axelband, USC/Rand/INCOSE
Lt. Col Ben Badami, Air Force/AQ RE
Mr. Ryan Boas, MIT
Dr. Phil Babcock, Draper Labs
Mr. Rich Blanchett, General Dynamics
Mr. Marion Butterfield, Boeing
Dr. Gary Caille, Naval Research Adv Comm
Mr. Luke Campbell, NAVAIR
Mr. Greg Carithers, Northrop Grumman
Dr. Dale Carlson, GE AC
Dr. Harry Crisp, Virginia Tech/INCOSE
Dr. Bill Crossley, Purdue University
Ms. Marty Evans, Air Force/ACE
Mr. Michael Fabrizi, The Aerospace Corp
Mr. Bill Forthofer, Pratt & Whitney
Mr. Sandy Friedental, Lockheed Martin
Mr. Thomas Gayheart, L-3 Communications
Dr. Benjamin Goldberg, Pratt & Whitney
Col Stephen Gourley, AFRL
Ms. Antoinette Gurvin, General Dynamics
Ms. Sheree Havlek, Raytheon
Mr. Thurmon Hass, NRO
Dr. Daniel Hastings, MIT
Dr. Jasjit Heckathorn, Draper Labs
Dr. Rick Hefner, Northrop Grumman
Dr. Dwight Holland, Human Factors Assoc
Mr. Bruce Jacobson, Northrop Grumman
Dr. Rashmi Jain, Stevens Institute
Dr. Stephen Johnson, Raytheon
Mr. Steve Kapurch, NASA
Ms. Catherine Keller, Raytheon
Mr. Jim Kindle, Northrop Grumman
Mr. Robert Koppelman, Northrop Grumman
Dr. Valerie Lang, The Aerospace Corporation
Mr. Mark L'Ecuyer, DCMA
Dr. James Linnehan, Army
Mr. Andy Loconto, General Dynamics
Mr. Robert Jelen, Northrop Grumman
Mr. Steve Johnson, Pratt & Whitney
Mr. Jeff Loren, Air Force/AQRE
Ms. Michelle McVey, SRA Intl
Mr. Sheldon Margolis, Lockheed Martin
Dr. Mike McCoy, Boeing
Col Mike McGinnis, West Point
Dr. Hugh McManus, MIT/LAI
Dr. Abe Mielich, Lockheed Martin
Mr. Jeff Mucha, Lockheed Martin
Mr. Noel Nightingale, LAI
Mr. Jon Ogg, Air Force/HQ AFMC
Mr. Scott Palmer, General Dynamics
Mr. Ken Ptack, NDIA/INCOSE/NG
Mr. Sigmund Rafalik, NAVAIR
Dr. Eric Rebentisch, MIT/LAI
Mr. Matt Richards, MIT/LAI
Dr. Donna Rhodes, MIT/LAI
Mr. Chris Roberts, BAH
Mr. Garry Roedler, Lockheed Martin
Mr. Adam Ross, MIT/LAI
Mr. Richard Rumpf, Naval Research Adv Comm
Mr. Jim Schier, GEIA/Northrop Grumman
Mr. Bill Schoening, Boeing
Ms. Sarah Sheard, SPC
Mr. Bob Skalamera, OSD AT&L
Mr. Dennis Schwarz, Boeing
Dr. Bob Shishko, JPL/NASA
Dr. John Snoderly, Defense Acquisition U
Dr. Bob Swarz, MITRE
Mr. Vic Tang, MIT
Mr. James Toth, NAVAIR
Mr. Mike Tuzzeo, Raytheon
Mr. Gary Van Oss, Air Force/ASC
Dr. Cheryl Walton, Off of Assist Sec Navy RD&A
Dr. Annalisa Weigel, MIT
Dr. Stan Weiss, Stanford University
Mr. Ryan Whitaker, MIT
Mr. Mark Wilson, Air Force/CSE
Dr. Michael Winter, Pratt & Whitney

Appendix B. Preliminary -- Key Questions Systems Leaders Must Ask

Workshop Results: *Each focus group developed a set of key questions that systems leaders need to be asking their engineering team in order to encourage engineering for robustness. An initial candidate set of key questions is listed below.*

Next Steps: *An action team has been formed to further elaborate these questions to produce a reference booklet for use by systems leadership, "**Key Questions Systems Leaders Must Ask**". Subsequent to development of these questions, the action team will work to develop the set of responses that systems leaders should be expecting when such questions are asked.*

Key Questions -- Systems Architecting

- What are your key (domain specific) parameters of robustness?
- What changes are expected that will impact the system architecture (e.g., threat changes, technology changes, CONOPS changes, environmental changes, Op tempo changes, scalability, etc.)?
- What assumptions is your architecture dependent on? What happens to the architecture if these assumptions change?
- What are the considerations for 'robustness' during concept development phase?
- What are your current practices for systems architecting that enable robustness?
- What analysis needs to be conducted, and how can architectures be evaluated for robustness?
- What have you done to ensure coherence of your systems architecture?
- How are you implementing information sharing and access to your architecture model to the stakeholders who need it? What elements are proprietary and does this result in any issues for other stakeholders in the program?
- Does your architecture definition include operational, system, technical?
- Describe how the system architecture will be audited/assessed? Who is the chief architect and what are his responsibilities and authorities on this program?
- What are the key attributes in "spiral one" that enable an extensible systems architecture?
- What Systems Architecting metrics will you use? How do you define them?
- What is the range of variation on the top three parameters on your requirements?
- How are you evaluating the scalability or expandability of the architecture of the system?

Key Questions -- Systems Development

- What is your approach for design for robustness? How will you accommodate requirements changes and technology changes (both anticipated and unanticipated)
- Does your design consider "robustness"? How are you measuring and reporting this? What are the specific deliverables?
- What is your risk management strategy? How are budgetary risks for evolutionary acquisition being addressed?
- What are the critical success factors for robustness of the overall system?
- What strategies can be used for subcontracting to ensure the delivered product will be robust, and align with overall system robustness strategies?
- What are the implications for modeling and simulation, testing, experimentation, and other activities?
- What leading indicators can be used to build confidence in the robustness of the solution?
- What is your approach for ensuring interoperability now and in the future? How will you decide which external systems not to interoperate with?
- How are you evaluating compatibility of spiral concepts and any impact on the baseline system?
- How do you accommodate technology insertion into the system? What methodology are you using to assess the maturity of the technology being proposed for the solution?
- How will you show how well you accommodate changes in the operational context?
- How are you going to model the system early to ensure robustness? How are the models and the modeling process going to evolve it through the life of the system?

- How are you managing the operational risks that will occur after product completion?
- What types of assessments and testing are being used to evaluate success in new concepts or technologies used in the development? (are you running pilots, e.g.) (related to spiral)
- How are you going to evaluate alternative requirements (capabilities) to determine a set that will lead to a viable set of requirements to which we can design. (pre-Milestone A)
- For a major SoS development, what extensions are being made to the classical SE process to account for increased number of stakeholders, dependencies, and the achievement of an overall best design?
- What are you sub-optimizing at the subsystem or component level in order to optimize at the 'global' level?
- What ongoing reviews/analyses are planned to ensure ongoing balance and trades of technical (including robustness), cost, and schedule?
- What are your limiting factors to flexibility, scalability, schedule, cost – and why?

Key Questions -- Sustainability

- Is sustainability being considered at all phases of system acquisition and design?
- Does the systems engineering plan reflect the importance of sustainability?
- Is sustainability being given appropriate weight and consideration in trade studies?
- Are contracts being written to emphasize/incentivize sustainability as a key lifecycle performance parameter (question for MDA to ask)?
- During planning and development phases, what are the effective strategies and approaches to ensure the robust solution will be supportable and affordable during sustainment phase?
- What are the critical success factors for ensuring continued growth in capability will be feasible?
- What leading indicators can be used to build confidence in this? What analysis needs to be conducted to support decisions?
- How will you ensure adequate suppliers to develop, maintain, and operate the system throughout its lifetime?
- Are all stakeholders educated on how to understand and appropriately evaluate sustainability considerations in system design?
- In meeting performance requirements, have you considered human factors, maintainability, and accessibility? What role will sustainment IPT/team play in selection of hardware/functionality?
- What are the strategies for sustainment (e.g., make each subsystem last for 30 years; fix once and replace; etc.)?
- What are the weakest links of reliability/durability?
- What is your software development plan for the full lifecycle (e.g., 25 years+) of the program?
- Does the contract provide incentives for lifecycle performance by suppliers/developers?
- What new hardware technology are you using in the system, and what is your plan for maintaining and sustaining it? What is your plan for sustaining software and system interfaces in the face of changing standards over the system life?

Key Questions – Organizational Factors

- What is your organizational structure, and what is your process for determining what can go wrong? What is your plan for maintaining long-term program management, and how will any hand-offs in leadership be handled?
- What measures are in place to provide insight into risk of inadequate SE performance?
- If there are incentives for robustness, what are the criteria for success or failure?
- What are the current challenges and inhibitors to systems engineering for robustness in the acquisition and engineering organizations on your program?
- What organizational, staffing, and process changes could accelerate the use of engineering for robustness on this program?
- What incentives can be used to encourage engineering for robustness?
- Do you have formal SE development and mentoring for employees?
- What is the SE approach used and is it effective, why or why not?
- What are your limiting factors to flexibility, scalability, schedule, and cost?
- What is your process for driving robustness throughout the supply chain?

- What are the budgetary risks for evolutionary acquisition being addressed?
- Does your program IPT structure internalize the value of sustainability, and does the end user (operational command) have a seat on the systems IPT?
- How are SE processes flowed down to 1st and 2nd tier suppliers?
- What best practices are being used to ensure the robustness of the product? Do you have a best practices compendium and is it shared throughout the supply chain?
- Is there a rotation plan for key SE employees within the system/mission area to develop and share expertise? Is a formal SE mentorship/development plan in place?
- Who in your organization has the SE authority and skills to ensure robustness of the system solution?
- Do the WBS and organizational structure align to support robust product development?
- How are stakeholders identified and represented within the IPTs?
- What is the plan and who is the authority for managing technical and independent reviews?
- Does the SEP for the program adequately address external interactions and interfaces (dependencies) that have the potential to impact successful design, development, and deployment?
- Have the programs and teams established how they will document and communicate risks, issues, actions, decisions, review findings?

Key Questions – Emerging Methods

- What methods will be used for requirements change, and how are changes tracked and accommodated?
- What methods will be used to integrate new technologies, and how are technology changes tracked and accommodated?
- What methods will be used to develop/evaluate design alternatives? How are evolution paths identified, evaluated, and chosen?
- What methods will be used to ensure SoS issues (e.g. emergent properties, interfaces) are effectively handled?
- What risk analyses and trade studies were used for requirements flowdown and allocation (including uncertainty analysis)?
- What methods were used to assess requirements growth, budget, and design margin consistency?
- How are these methods integrated into current program practices?
- How are your methods validated?
- How are methods evolved or developed as needed?
- What budget reserves and design margins are allocated to system evolution? How are budgets and margins defended?
- How have you estimated the costs for implementing robustness methods?

Appendix C. Additional Perspectives and Recommendations of Workshop Participants

Workshop Results: *Each focus group was asked to highlight any recommendations for improving the current version of the AF Guide on Engineering for Robustness. The groups also highlighted recommendations for ensuring good systems engineering practice and the overall SE Revitalization effort.*

Next Steps: *An action team will examine the workshop focus group findings, the suggested recommendations, and the outcomes from the various action teams. Useful and appropriate information and recommendations will be incorporated into the next version of the guide, and also provided to other initiatives and working groups for consideration.*

General Comments and Observations

- Many participants felt that the workshop should be held on a periodic basis to continue the dialogue on this important subject.
- We see ambiguity/vagueness of "robustness" in RFPs and contracts. RFPs often focus on solutions rather than the needed capabilities.
- There is pre-mature establishment of requirements right at the start before trade space exploration.
- Workforce instability of systems engineering in a program has a negative impact.
- We face an impending loss of systems engineering subject matter expertise due to aging SE population with insufficient replenishment. We are inhibited by the erosion of workforce, diminishing manufacturing capability, lack of people entering engineering, changing cultural attitudes towards instant gratification.
- The lack of cross-training between systems and software practitioners is an inhibitor to effectively working together, and sometimes results in software engineering trying to operate independently of system engineering.
- Current emphasis by senior leadership on system engineering may disappear if not completely institutionalized. Systems engineering will be threatened if the corporate response to systems engineering effort is limited to responding to current USAF focus and doesn't become institutionalized.
- Company business objectives and measurements are often inconsistent with delivering a robust solution (financials much more important to company executives than elegant engineering solution)
- We manage to work products vice intellectual content.
- Business decisions of customers inhibit the application of robust processes.
- Pre-mature implementation or inappropriate implementation of systems engineering tools can threaten the perceived value of such tools in engineering practice. The over-emphasis of "exotic technologies" when not the most optimal solution to the problem can threaten the robustness of the solution.
- Other acquisition authorities have not stepped up to the robust SE challenge yet to define a specific policy. Also, there is a lag between policy and implementation by industry.
- There is an overall lack of availability of experienced systems engineers to meet the present need. There is erosion of SE knowledge in both government and industry – especially in government. The FFRDC and SETA support is dwindling.
- Current contractual mechanisms do not adequately accommodate requirements changes.
- Robustness is limited by people who see requirements as fixed rather than changeable
- The organizational mind-set is an inhibitor – we need a transformation to thinking in terms of open systems and flexibility, with concrete requirements for robustness.
- Existence of professional societies like INCOSE and NDIA are important.
- More workshops like this are needed to address the issues.
- There are not enough people trained in "contemporary" best systems engineering practices
- Government is an enabler of the revolutionary changes
- Good emphasis on supportability/sustainment aspects of program in awarding new contracts
- Moving toward policies and guidance – more what and less how

Additional Recommendations for Good Systems Engineering

- Systems leadership need to identify/quantify/publicize consequences of not addressing robustness in systems programs and not performing adequate systems engineering. And, leadership needs to identify/publicize examples of current program successes, including public awards, recognitions and rewards for good systems engineering.
- It is recommended that specific working groups for both government and industry be formed to collaborate on improving systems engineering for robustness practices.
- We need to continue to focus on development of government and industry personnel who understand how to achieve robust SE solutions. And, additional effort is needed to make government personnel aware of SE training opportunities.
- We need to develop and define the standard RFP language with expected activities and products that will result in effective application of engineering for robustness practices.
- Government needs to ensure that the contractual incentives for robustness are in place.
- We need to develop strategies to accelerate maturation of SE engineers who can address the needs and challenges of contemporary systems.
- There is a need to establish/improve the government and industry SE career paths, and requisite training & mentoring.
- We need to develop strategies for organizing programs to encourage robust SE for systems and system-of-systems.
- There need to be incentives for contractors who contribute the most to the robustness of an overall solution.
- Organizational change in government is needed to bring together the stakeholder communities and remove arbitrary boundaries.
- We need both vertical and horizontal population of SE in the organization
- We need both short and long term strategies for the “incubation” and development of SEs
- We also need to think about robustness of the product as the ability to easily respond to unforeseen operations challenges/applications or technological forces.
- We need to establish robustness champions at all levels in the program – with enforcement, incentives, rewards
- We need to give robustness a context in the technology roadmaps, technology strategies, etc.
- Long term relationship with contractors and suppliers can be beneficial for good systems engineering, and we need to rate contractors at least partially based on sustainability of product.
- Accelerated development cycles limit the up-front analysis and trades that can be done.
- We lose SE funding during program because of cost pressures to underestimate. Also, our current practices make it too easy to defer sustainment/support costs to future.
- There is an unwillingness to let loose of total control as in collaborating systems in which others can make unilateral decisions.
- The required robustness of systems today may exceed the capabilities of our present methods and tools.
- We lack the ability to accurately predict lifecycle costs in complex systems/SoS when program data is not always tracked appropriately.
- We do not clearly understand the challenges and strategies for SoS versus system. We are not good at seeing the cause/effect relationships in long lifecycle programs. Results from operations research, test and development do not effectively get fed back into the systems design and acquisition processes. Multi-objective optimization is available to examine performance objective trade-offs.
- Robust design and optimization under uncertainty are developed for component-level design.
- We rarely model requirements and need improved approaches and tools for doing so. Modeling and simulation tools need to be created, and then implement effectively. Current practices lack the ability to specify robustness requirements and we lack the standards, methods and tools for system/SoS robustness analysis.
- Define system characteristics that contribute to complementary systems performance and ability to substitute for other systems in the force structure, supported by a database that can be used during design. New methodologies and tools will provide the opportunity for more rigorous, quantitative upfront SE, resulting in improved system lifecycle cost and performance. Extending/leveraging methods from other domains and disciplines can contribute.

- Improve dissemination of verified SE best practices/ lessons learned from 'failures' will result in better engineering practice. We need research on the organizational governance for SoS
- Online collaboration encourages data exchange/communication—could incredibly help up-front part of process
- Creation of a methodology for evaluating potential future states thus improving adaptability & flexibility for robust systems
- Modern technology allows for enhanced capabilities for more rapid/accurate assessments, prototyping, and feedback in evolutionary programs
- Technology and database capacity has opened the door for better FoS/SoS assessment tools not previously within technical reach.
- Technology now exists for better data fusion and visualization, and needs to be considered as a high priority when interacting with complex data sets
- As systems increase in complexity, there is often too much uncertainty/ lack of credibility in the scenarios developed during concept phase.
- We are not easily able to converge on a shared value proposition and set of requirements that are technically achievable, acceptable cost and risk, and meet enterprise stakeholder/users needs.

Recommendations for Updating the Guide

- The guide needs to emphasize more strongly technical leadership in addition to technical management skills. Clearly define roles, responsibilities, and accountability in the guide.
- The guide should discuss the need for SE work products (specs, trade studies, analyses) and requirements over the product lifecycle to be respected as much as the end product design (and they need to be created with this in mind). That is, systems engineers really need to make sure that their products are usable and easily understandable to design engineers, and the guide should put appropriate emphasis on this.
- The guide should have added emphasis on the SE role in supplier management and sustainment.
- It is recommended that the guide use an active voice when talking about SE activities—gives more emphasis on the fact that systems engineers are leading the technical effort.
- The guide should better define robustness in practical terms, and should address how it is measured and the criteria for assessing.
- The guide needs to address needed changes in procurement procedures for use of robustness criteria within evolutionary development.
- The guide needs to recognize horizontal robustness (systems of systems involving multiple contractors), and strategies for these highly complex endeavors.

Appendix D. Workshop Contributions to the SE Research Program

Workshop Results: *Each focus group highlighted a set of questions where further research and system studies are needed to improve engineering for robustness practices and methods.*

Next Steps: *LAI will elaborate these research questions and these will be incorporated into the broader systems research agenda.*

The workshop has underscored the need for more systems research, as well as for better synthesis and communication of research findings and case studies. A strong research program is driven by a research agenda that is a shared vision of government, industry, and academia. Today's systems engineering research is not seen as *basic research,* and therefore funding is not readily available. Alternative strategies for increasing the research in systems engineering are needed with collaboration on all impacted stakeholders. A systems research agenda is one important component.

LAI will continue its efforts to develop an expanded systems research agenda, in collaboration with professional societies such as INCOSE. The workshop contributions will be incorporated into this effort. The LAI Educational Network SE group, comprised of leading university faculty and researchers, will link past or ongoing research studies to the agenda. Further efforts are needed to develop a strategy for furthering systems research and communication of its results.

INCOSE has a research center of excellence and has recently initiated a "research network" of PhD students mentored by INCOSE Fellows (MIT/LAI students are part of this network). The workshop findings and deliverables will be shared INCOSE and other professional organizations to assist in furthering research directions and projects. The research studies of graduate students participating in this network will be mapped to the research agenda, and the network will look for approaches for cross-cutting research and collaborative opportunities.

The LAI compendium of relevant systems engineering research studies and findings has been published on the LAI website. A paper highlighting key findings of the workshop and implications for research is planned for the March 2005 Conference on Systems Engineering Research (CSER).

Systems Engineering Research Perspectives of the Workshop Participants	
What do we do well today? Many universities now have PhD students doing research on systems engineering. Research is also being done in industry and government.	**What are we not doing well today?** We lack a shared vision for systems research, and while there has been work on defining research that has been done, we lack a good overall systems research agenda. Further, we do not have a good way to link systems engineering researchers and integrate individual projects into broader systems research.
What are the inhibitors or barriers? Systems engineering research is not typically viewed as 'basic research' or as an area of 'hard' science. Therefore it is very difficult to obtain research funding. In regard to robustness, long term research on robustness is needed, but not being undertaken to the degree that is needed (some perception that this is the fad of the week).	**What are the improvement opportunities?** There is a rich set of topics that systems engineering research can address, and there growing interest in such research in industry and government. The workshop has resulted in a set of research questions which can contribute to the evolving research agenda. There are also opportunities for developing good case studies (and the AF Center for SE has begun such an effort).
What are some of the important research questions? **<u>Systems Engineering Process</u>** • What are common attributes of the systems engineering process for particularly robust systems? • What are the SE risks and consequences of an accelerated procurement? • What can be done to create 'smart' tools/techniques (esp. 'smart' w.r.t. software) for implementing, evaluating, and improving the SE process? • How do we extract the most information from past failures and successes? How did any of these affect policy? Were any of these policy changes still in place 5 years later? 10 years later? Was there a 'pendulum' effect? • What is the value added by robust approaches to SE? How can this be quantified? Could this be done by analyzing the cost and benefits of having done the SE different (with an eye for robustness) for well-known failures? • What approaches are needed to ensure options/flexibility in the upfront systems engineering?	

- How can we perform a quantitative assessment of historical program data (current and when SE Processes were more prescriptive) to validate expert opinion regarding policy and training?

Systems Architecting

- What are the domain specific characteristics of robustness?
- How can you use mathematical techniques to quantify/evaluate robustness of the system architecture?
- How can the Systems Architecting metric set be characterized?
- What is the impact of system robustness on cost and mission effectiveness of SoS?

Systems Development

- What has worked in the past to tie the user needs more directly to the developer? (i.e. How do achieve direct communication with the user in order to develop the right product the first time?) What methodologies or tools can be created to help this? How can online collaboration help accomplish this?
- What can be done to develop better human-system interface testing procedures? (e.g. flight test and other complex person-rated systems)
- How can we better communicate lessons learned from database evaluations of incidents, mishaps, & usability studies to the front end of the process for all future development of similar systems?
- Can tools & methodologies be developed for determining effective system life and planning system upgrades?
- When should one create a disposable system versus a robust one? What metrics help determine this?
- What case studies should be developed for use in education systems engineers – for example, network-centric warfare; B-52 vs B-58; Software-compliant architecture?
- What is the impact of system robustness on the cost and mission effectiveness of the SoS/FoS?

Organizational Factors

- What are the proven measures and leading indicators for robustness (not one-size-fits-all)?
- What are the short- and long-term strategies for accelerating the development of competent systems engineers?
- What are effective organizational governance models for systems of systems and families of systems?
- What incentives can foster robustness of the overall system-of-system solution, rather than suboptimal robustness of the component systems?
- Is there a shared vision for long term success of the program, and how are these reflected in the overall acquisition and development plans?

Sustainment

- What cost models can be used to ensure adequate focus on robustness considerations for the sustainment phase?
- What models and simulations are useful for analysis of impacts on system sustainment and full lifecycle operational effectiveness?
- What are the lessons learned and best practices that come from programs such as nuclear weapons (highly reliable over long duration)?
- What strategies and practices from commercial sustainment practices can improve defense program practices?
- How are supportability needs and requirements effectively established during the front-end program effort?
- How do new technologies (e.g., nanotechnologies) impact systems sustainment? How do these contribute to sustainability of systems?
- How can we prevent the "normalization of deviancy" in long lifecycle programs?
- What are the incentives for robustness? What are the criteria for success/failure?

Emerging Methods

- What are the domain specific applications of real options, such as in space missions?
- What can we learn by applying real-options to historical data?
- How can be mature and validate advanced methods of analysis and assessment?
- What new methods/extension of existing methods are needed to effectively handle SoS challenges?
- What methods will be used to handle SoS interactions/interoperability for your system?
- How do we quantify the value of applying SE methods to ensure robustness of the system solution?
- How do we best insert new methods in current/future programs?
- What methods are used to identify robustness alternatives (e.g., embedded real options)?
- What methods are used to evaluate the robustness alternatives (in systems context? In SoS/FoS context?)? How are preferred alternatives selected?
- What methods/tools will be used to validate that the design is capable of meeting the robustness requirements? What is the budget and design margin reserve that allows for system evolution?
- How have you validated the results of your trade studies?

Appendix E. Workshop Findings Relevant to LAI's Value-Based SE Framework Initiative

Many recent studies of the failures on systems programs point to insufficient application of the systems engineering process. The reality is that SE process application is constrained by program budget, schedule, and human resources. While models like CMMI provide insight on characteristics of high-maturity systems engineering organizations, we lack models that communicate the highest value systems engineering activities that programs need to focus on. Further, these high-value aspects are human-intensive, so are intimately linked to organizational factors. A new framework to capture value-based attributes is recommended to drive good engineering behavior.

The LAI Educational Network's Systems Engineering Group, comprised of leading university faculty and researchers, has undertaken an effort to develop a "Value-Based Systems Engineering Framework". The framework, when complete, will capture (and serve to keep focused attention on) the activities of systems engineering that yield overall highest value. The evolving framework will be shared with LAI members to validate the usefulness of the framework in driving good systems engineering, and is intended to become a useful tool for the wider systems community.

Value-Based Systems Engineering Framework Perspectives of Workshop Participants	
What do we do well today? We use frameworks to help guide the development of processes and organizations for engineering. Workshop participants noted that the CMMI and lean principles can help drive high value SE process application.	**What are we not doing well today?** We do not have a simple organizing framework that capture the high value activities of engineering as integrated with the organizational aspects of engineering. As an example, SE processes advocate risk identification, but there is a mindset in many organizations that identifying risks is a "bad thing" when what is needed is to bring risks forward to monitoring and mitigation. A clear framing of this activity is needed to characterize the engineering activity in context of the value it provides while recognizing the organizational factors.
What are the inhibitors or barriers? Good systems engineering is inhibited by the divergence of ideas on how and when to implement the SE process to achieve best value.	**What are the improvement opportunities?** A framework that can merge the existing standards would be a contribution. There are potential useful synergies of lean practices and systems engineering practices.