Systems Engineering and Integration for Advanced Life Support System and HST

Final Report
NASA Faculty Fellowship Program – 2004

Johnson Space Center

Prepared by:	Ali K. Kamrani, Ph.D.
Academic Rank:	Associate Professor
University & Department	University of Houston Industrial Engineering Houston, TX 77204

NASA/JSC

Directorate: Engineering

Division: Crew & Thermal Systems

Branch: N/A

JSC Colleague:	Donald L. Henninger, Ph.D.
Date Submitted:	August 31, 2004
Contract Number:	NAG 9-1526&NNJ04JF93A

ABSTRACT

Systems engineering (SE) discipline has revolutionized the way engineers and managers think about solving issues related to design of complex systems. With continued development of state-of-the-art technologies, systems are becoming more complex and therefore, a systematic approach is essential to control and manage their integrated design and development. This complexity is driven from integration issues. In this case, subsystems must interact with one another in order to achieve integration objectives, and also achieve the overall system's required performance. Systems engineering process addresses these issues at multiple levels. It is a technology and management process dedicated to controlling all aspects of system life cycle to assure integration at all levels.

The Advanced Integration Matrix (AIM) project serves as the systems engineering and integration function for the Human Support Technology (HST) program. AIM provides means for integrated test facilities and personnel for performance trade studies, analyses, integrated models, test results, and validated requirements of the integration of HST. The goal of AIM is to address systems-level integration issues for exploration missions. It will use an incremental systems integration approach to yield technologies, baselines for further development, and possible breakthrough concepts in the areas of technological and organizational interfaces, total information flow, system wide controls, technical synergism, mission operations protocols and procedures, and human-machine interfaces.

This report provides the summary of results based on the proposed SOW during the 2004 fellowship at NASA's Johnson Space center for NFFP. These tasks were:

1. Benchmarking and the evaluation of systems engineering processes in order to identify best practices and lesson learned.
2. Propose a SE process template for the identification of functional requirements and its decomposition for human life support systems.

INTRODUCTION - ADVANCED INTEGRATION MATRIX (AIM)

The Advanced Integrated Matrix (AIM) project attempts to provide SE&I services to highly advanced and complex projects (e.g. missions beyond Lower Earth Orbit or LEO) through ground-based testing and integration. The goal of the AIM is to develop the enabling environment and tool for gap analysis and commonality. The roadmap to AIM is through incremental implementation. The incremental approach evolving from a single-enterprise into a multi-enterprise, multi-center concern focused on developing and testing integrated mission concepts. AIM will initiate with projects with low level of complexity for integration and testing and then gradually evolve into a full mission scenario through "***fly the mission on the ground***" concept. Figure 1 conceptualizes this concept.

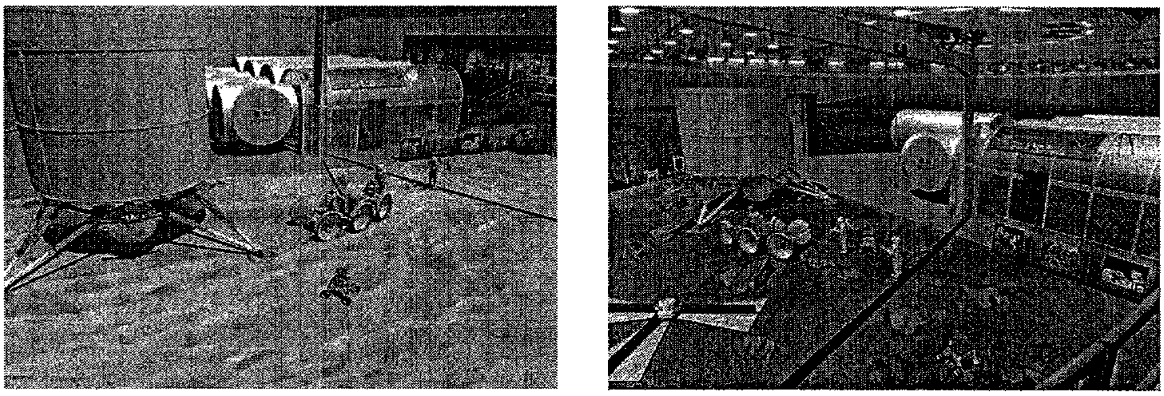


Figure 1. Moon and Mars "*fly the mission on the ground*" Configurations[1]

This incremental approach will generate the lessons learned and baselines for further designs of more complex systems. The possibility of identifying new breakthrough managements concepts and technology to support interfaces, information flow and sharing, managements, controls, operations and procedures, and man-machine interfaces are the goal of the this approach. This would require participations from different programs in the agency. AIM will[2]:

- Address system-level integration and interface issues to support agency commitment to an exploration mission
- Investigate issues common to multiple vehicles, architectures, and mission scenarios, and develop solutions in a scalable format
- Aggressively pursue participation from academia and other NASA Centers to address Agency's Strategic Plan.

AIM will collect the scientific and technological knowledge of individual projects into an integrated ground-based test environment where system-level interactions are studied and optimized for commonality, performance efficiency, cost and mass savings. The Office

---

[1] D. Henninger, *Integrity: A Program Concept*, Johnson Space Center, NASA, 2002.

[2] G. Thomas, *AIM Project Quarterly Report*, AHST Program, Johnson Space Center, NASA, 2003.

of Biological and Physical Research (OBPR) has authorized initiation of the formulation phase. The purpose is to identify and solve system-level integration issues for exploration missions beyond Low Earth Orbit through design and development of a ground-based facility for developing an integrated system for joint human-robotic missions.

PART I – SYSTEMS ENGINEERING PROCESS AND GENERIC MODELS

Past experience has shown that lack of planning and clear identification of objectives has been the major problem associated with the design and development of any complex system. This approach has resulted in a system's lack of performance and finally design failure. Traditionally, systems have been developed based on "***Deliver now and Fix Later.*** [3]" This process has suffered from lack of clear planning which resulted in failure and high cost of design modifications. In this scenario, requirements at the systems level were kept general in order to reduce complexity to allow for new technology integration. This has routinely evolved into last minute modifications that impacted the schedule and cost. Decisions made at the early stages of development life cycle will significantly impact the overall life-cycle including cost and system's effectiveness. Therefore, there is a need for a disciplined approach for integrated design and the development of new systems. In this case, all aspects of the development are considered early in the process and used for continuous improvement. Systems Engineering is "*The effective application of scientific and engineering efforts to 1) transform an operational need into a defined system configuration through the top-down iterative process of requirement analysis, functional analysis and allocation, synthesis, design optimization, test, evaluation and validation, 2) integrate related technical parameters and ensure the compatibility of all physical, functional, and program interfaces in a manner that optimizes the total definition and design, and 3) integrate reliability, maintainability, usability, safety, serviceability, disposability to meet cost, schedule, and technical performance objectives*[4]. Systems engineering is also considered a process for Managing Technology. System engineering process has evolved in seven different paradigms[5]. A summary of these processes are discussed below.

1. **Build–Test–Fix:** This method consists of three basic steps, *fabricate a design, test the system, and then operate.* This method is typically used for in-house software development where the customer is also the developer. It is considered to be a simple but effective approach. Although, it lacks the requirements analysis phase that makes it not suitable for any complex systems design.
2. **Staircase:** The Staircase method allows for better management and control of system development. This method is considered to be a systematic flow through the SE process. It is well suited for the developments of existing systems variants. In this

---

[3] Benjamin S. Blanchard, *Systems Engineering Management*, Wiely Interscience, 1998.

[4] Systems Engineering Fundamentals, Defense Acquisition University Press, 2001.

[5] Norman B. Reilly, *Successful Systems Engineering for Engineers and Managers*, Kluwer Academic Publishers, 1993.

case, already developed requirements are modified. The export version of a military aircraft is an example this concept. **R**equirements-**S**pecification-**D**esign-**F**abrication-**T**esting-**A**cceptance-**O**perate area steps in the staircase SE cycle.

3. **Waterfall:** This method improves the staircase method by adding feedback loops between successive stages as shown in Figure 2. Through these feedbacks, each stage is capable of gaining knowledge from the subsequent stages. The success of this model is dependant on understanding and processing revisions through feedback analysis.

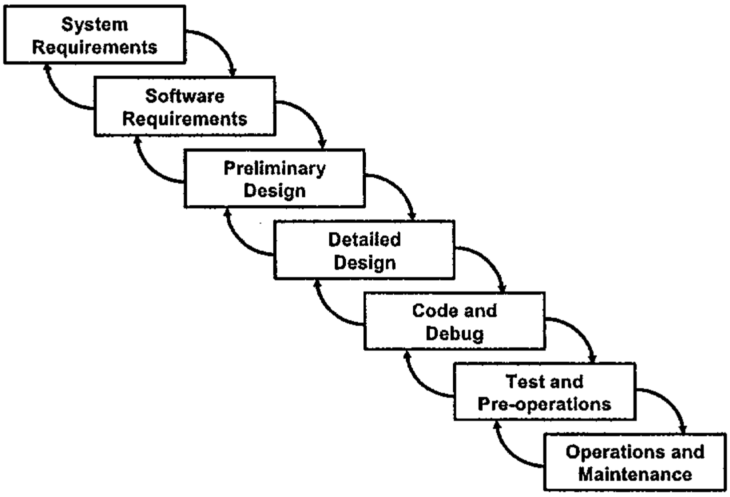


Figure 2. Waterfall Systems Engineering Process Model

4. **Early Prototype:** The early prototype process is an extension to the staircase with feed back cycle. This method is used when it is difficult for customer to identify requirements, but could recognize them through some model or prototype representation. The advantage of this method is due to direct interaction between stakeholders. Some of the difficulties with this approach are 1) the initial prototype could discourage the customer 2) it suggests an unattainable goals and 3) prototype design becomes the main objective rather than the actual customer's need.
5. **Spiral:** The Spiral method, as shown in Figure 3 is an extension to the early prototype concept. The primary advantage of the spiral method is the detailed development of requirements, specifications, and designs. The significant challenge for the spiral method is managing the prototype transitions. Some of the advantages are:
   - Risk-driven sequential phases with user involvement.
   - Considers highest risks issue first (Requirements understanding, Technical feasibility and System operations).
   - Cycles of risk-driven phases, spiral around and end with a final waterfall wrap.
6. **Rapid Development:** The success of this process dependent on fast-paced innovation (**RSDFTAO— RSDFTAO…**) while completing multiple small starts to the final system. This process requires cross-functional teams with the ability to work across the functional boundaries.

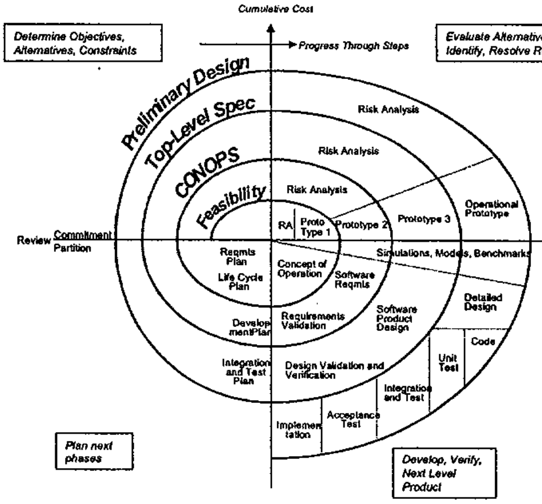


Figure 3. Systems Engineering Spiral model[6]

7. **Integrated:** Integrated or concurrent development method consists of cross-functional teams with members from all of the functional areas working closely together, sharing details of their portion of the design as it progresses, and developing all aspects of the system simultaneously. The result is overlapping and managing the overall life cycle. Concurrent Engineering (CE) is defined as the systematic and integrated approach to systems life cycle design. CE is also known as the *Design for Life Cycle* model. Concurrent engineering is the implementation of parallel designs by cross-functional teams including suppliers. Without empowered team members and the free flow of communications, this method will not function. Figure 4 illustrates an overview of the integrated SE infrastructure. Table1 lists partial comparison among these models.

A model that is typically used to define the critical elements of SE process is the Systems Engineering Capability Maturity Model (SE-CMM)[7]. These elements consist of activities which define '*what*' has to be done. Table 2 lists these tasks. Tasks for design and development are listed in engineering group, project elements provide the management infrastructure and finally the organization elements provide the business infrastructure to support systems engineering effort.

---

[6] B. W. Boehm, *Spiral Model of Software Development*, Tutorial Software Project Management edited by R. H. Thayer and M. Dorfman, IEEE Press, 1988.

[7] Systems Engineering Capability Maturity Model^{SM}, Version 1.1, Software Engineering Institute, Carnegie Mellon University, 1995.

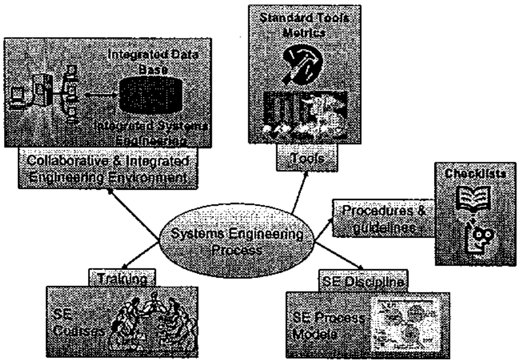


Figure 4. Integrated Systems Engineering Infrastructure

SE Paradigm	**Easy to Implement**	**Supports Prototyping**	**Early Customer Involvements**	**Ease of Engineering Changes**	**Meets Customer's Schedule**	**Requirement Driven**
Build-Test-Fix	++	+	-- --	--	+	--
Staircase	+	--	--	++	0	-+
Waterfall	-	--	+	+	--	+
Early Prototype	--	+	+	+	--	+
Spiral	-- --	++	+	+	+	+
Rapid Development	-- --	++	-- --	+	--	+
Integrated	-- --	++	++	-- --	+	++

Table 1. SEP sample comparison, strong (++), average (+), none (0), low (-) very low(--)

Engineering	**Project**	**Organization**
✓ Understand Customer Needs ✓ Derive and Allocate Requirements ✓ Analyze Alternative Solutions ✓ Evolve System Architecture ✓ Integrate System ✓ Integrate Disciplines ✓ Testing and Acceptance	✓ Ensure Quality ✓ Manage & Control Configurations ✓ Manage Risk ✓ Monitor & Control Technical Effort ✓ Plan Technical Effort ✓ Integrate Technical Efforts	✓ Coordinate with Suppliers ✓ Define SE Process ✓ Manage System Evolution ✓ Manage Systems Engineering Support Environment ✓ Continuous Improvement

Table 2. SE-CMM Model

SYSTEMS ENGINEERING SAMPLE PROCESS MODLES

"Vee" Process is widely used by many industries (Figure 5).

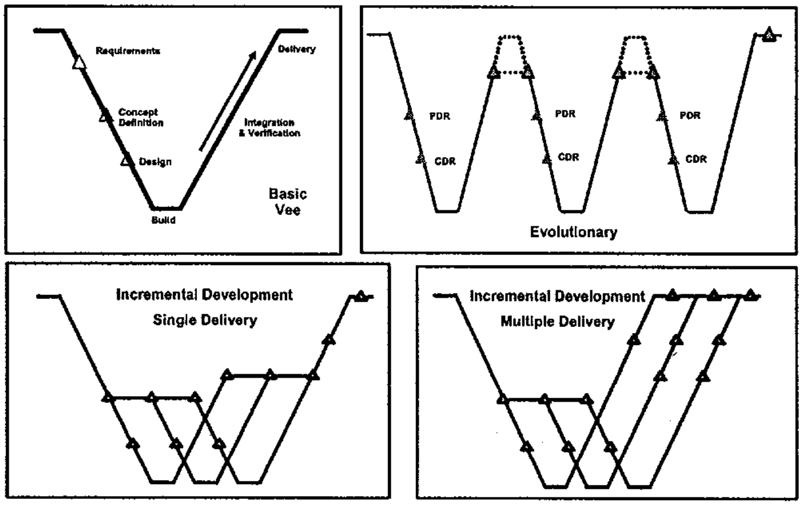


Figure 5. "Vee" Process as applied to NASA Projects[8]

This concept is based on the iterative and parallel processes on the left hand side that will manage the verification functions on the right hand side. Verification is completed in a serial fashion, resulting in minimal rework. This method is cost effective and improves the success of the project. It also provides the necessary infrastructure for alternative design analysis and selection. A system that fits the requirements with best performance, voiced by the stakeholders. It is believed that by using this approach the probability of design of a reliable and satiable system is high[9]. Within the "Vee" process, the ***3-Bubble Method*** (Figure 6) assures that the design performance and feasibility (schedule) are continuously compared with the requirements. This allows for analysis of alternative designs against the verified requirements.

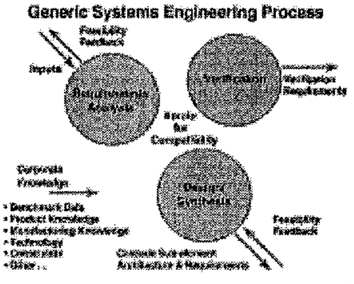


Figure 6. 3-bubbles method[10]

---

[8] K Forsberg, H. Mooz and H. Cotterman, *Visualizing Project Management: A Model for Business and Technical Success*, 2nd Edition, Wiley and Sons, 2000.

[9] Ford Design Institute, *Systems Engineering Fundamentals Course,,* Ford Motor Company, 2000.

[10] Ibid.

The International Council in Systems Engineering, ***INCOSE***, defines the Systems Engineering Process as *"... an iterative process of technical management, acquisition and supply, system design, product realization, and technical evaluation at each level of the system, beginning at the top (the system level) and propagating those processes through a series of steps which eventually lead to a preferred system solution. At each successive level there are supporting, lower-level design iterations which are necessary to gain confidence for the decisions taken. During each iteration, many concept alternatives are postulated, analyzed, and evaluated in trade-off studies. There are many cross-coupling factors, where decisions on one subsystem effect other subsystems*[11]." INCOSE model is illustrated in Figure 7.

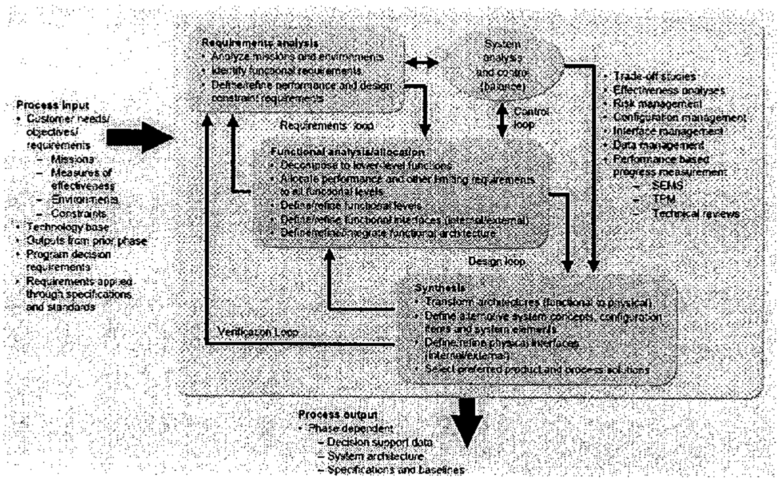


Figure 7. INCOSE Systems Engineering Model[12]

The Department of Defense (DoD) defines the systems engineering process as the transformation of the operational needs and requirements into an integrated system design solution through concurrent consideration of all life-cycle needs. This process will ensure the compatibility and integration of all physical interfaces and system definition and design reflect the requirements for all system elements (hardware, software, data, people, etc.). Finally, the SE process will identify and manage technical risks associated with the system development. Figure 8 illustrates the DoD SE process. ***Cost as an Independent Variable Concept (CAIV)*** is defined in Section 3.3.4 of DoD 5000.2-R, as:"*. . . a process that helps arrive at cost objectives (including life-cycle costs) and helps the requirements community set performance objectives. The CAIV process shall be used to develop an acquisition strategy for acquiring and operating affordable DoD systems by setting aggressive, achievable cost objectives and managing achievement of these objectives. Cost objectives shall also be set to balance mission needs with projected out-year resources, taking into account anticipated process improvements in both DoD and defense industries.*" Cost in this process is a constraint. Identification and use of viable range of alternatives with knowledge of real and potential impacts, is essential for making

---

[11] International Council on Systems Engineering (INCOSE) SE Handbook Working Group, 2000.
[12] Ibid.

the right decisions to meet stakeholders VOC while minimizing the Total Ownership Cost (TOC).

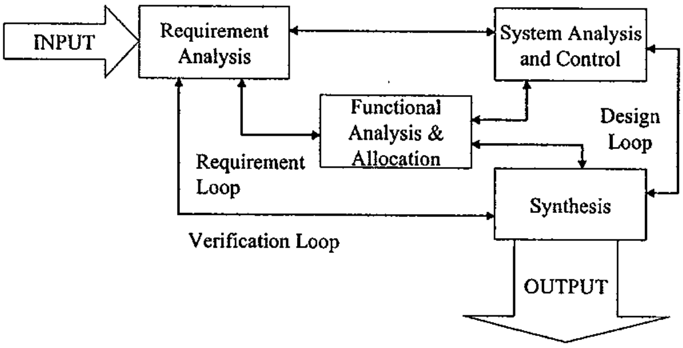


Figure 8. DoD SE Process Cycle[13]

CAIV principle, as proposed by USAF, is further decomposed into five pillars[14]. Figure 9 illustrates these five pillars.

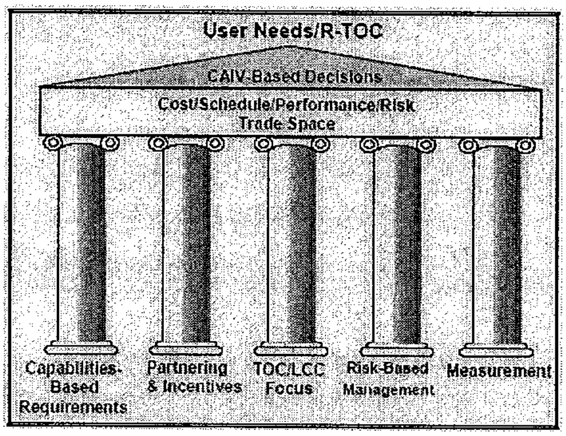


Figure 9. CAIV Process Pillars[15]

CAIV is based on capability-based requirements. In this case, user must first define "what" the system needs to do and how subsystems are allocated. Cost Performance Integrated Product Team (CPIPT) is a major component of the CAIV process. This team performs cost-performance-schedule tradeoffs leading to CAIV-based cost, performance, and schedule objectives. The CPIPT and stakeholder work closely together to resolve issues and decide on the final range and objective values for schedule cost and

---

[13] Systems Engineering Fundamentals, Defense Acquisition University Press, 2001.

[14] Col. M. A. Kaye (USAF), Lt. Col. M. S. Sobota (USAF), D. R. Graham, A. L. Gotwald, "*Cost as an Independent Variable (CAIV) Principles and Implementation*," American Institute of Aeronautics and Astronautics, 1999.

[15] Ibid.

performance. The total life cycle cost is closely monitored. TOC in CAIV is LCC. Risk management is an important part of the CAIV process. Program management and means for measure of progress assures the success of CAIV process. **Simulation-Based Acquisition Concept (SBA)** is the integrated and collaborative approach to systems design and through computer–based modeling and simulation. SBA concept is based on the DoD acquisition reform initiative. The new process as defined by DoD 5000.1, 23 Oct 2000 consists of "*an acquisition process in which DoD and Industry are enabled by robust, collaborative use of simulation technology that is integrated across acquisition phases and programs.*" SBA concept is based on collaborative engineering concept and environment[16]. Industrial partners, academia experts and government agencies will closely collaborate using COTS, technologies, developed methodologies and resources. This will reduce the development time and cost associated increased performance and functionality. Five principal architectural concepts used for SBA implementation are:

1. Collaborative Environment
2. Collaborative Environments Reference Systems Architecture
3. Distributed Product Descriptions
4. DoD/Industry Resource Repository
5. Data Exchange Format

SBA is not the replacement for systems engineering process. It is a distributed and integrated approach to design using the systems engineering principles. It is a modeling and simulation (M&S) technique used to support managers during their decision making process. It must maintain the integrity and security of all shared data including responsibility and accountability at all levels of proprietary and security.

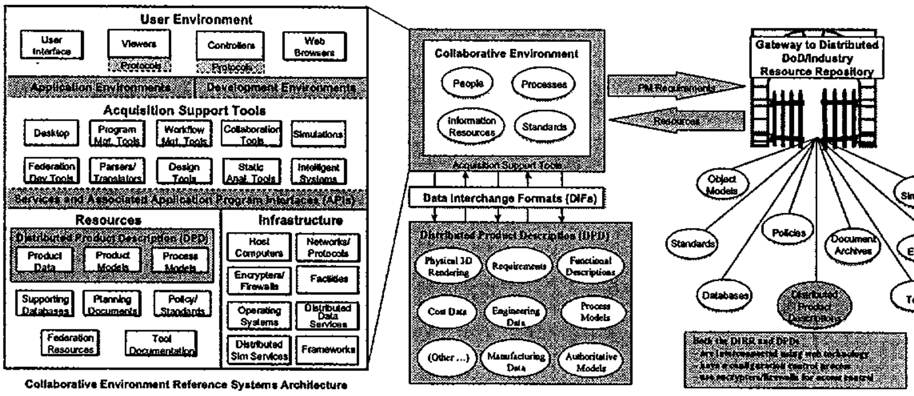


Figure 10. SBA infrastructure[17]

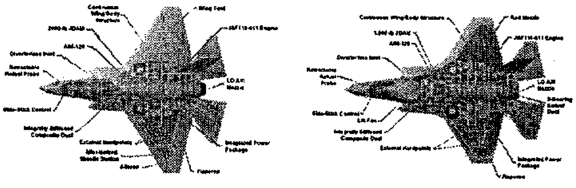
---

[16] Simulation Based Acquisition; A New Approach, Defense Systems Management College Press, 1998.

[17] J. E. Coolahan, F. T. Case, Lt. Col. R. J. Hartnett, Jr., (USAF), "*The Joint Strike Fighter (JSF): Strike Warfare Collaborative Environment (SWCE),*" Proceedings of Fall Simulation Interoperability Workshop, 2000.

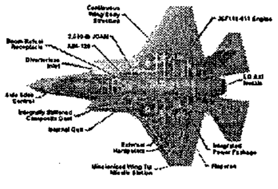
THE JOINT STRIKE FIGHTER PROGRAM

JSF program goal is to develop an affordable family of multi-role attack aircraft with high commonality. JSF has been described as a supersonic, single-engine, single-seat airplane with F-16/F/A-18 class performance and stealthy. The three JSF variants are a conventional takeoff and landing (CTOL); a carrier-based attack (CV) variant and a STOVL replacement. The Air Force may also buy some STOVL variants to replace its A-10s. (Figure 11).



CV Configuration

STOVL Configuration



CTOL configuration

Figure 11. Lockheed Martin JSF Family for Next Generation of Military Fighters

Modeling and simulation (M&S) concept has been significantly used for the JSF program through Program Definition and Risk Reduction (PDRR) to integrate warfighters and maintainers into the development process early in the design life cycle. The objective is to reduce requirements changes and development costs. JSF program charter focused on six key initiatives:

- Establishing an integrated team of users and developers
- Facilitating evolution of fully developed and validated operational requirements
- Evolving requirements over time
- Reducing development, procurement, and support costs
- Performing tradeoff analyses of critical user defined performance parameters
- Conducting unprecedented levels of simulation

Within the four major JSF requirement (lethality, survivability, supportability, and affordability) 34 attributes are identified. These are, acquire the target, generate sorties, situational awareness, countermeasures, ID the target, weapon/sensor integration, accurate navigation, mission level intelligence, pass/receive timely information, assess battle damage, route planning, emissions control, maintainability, carrier suitability, inter operability, basing flexibility, all weather/night capability, multi-role capability, weapon carriage versatility, mission flexibility, accuracy, radar cross section, range, logistic footprint, payload, infrared signature, speed, maneuverability, electro-optical signature, redundancy, hardening, acoustic signature, reliability, and ferry range. The JSF attributes are the combination of functions, operational flexibility, operational constraints, and parameters. Simulation modeling and virtual prototyping has allowed the Joint Strike Fighter (JSF) concept demonstration for assembly to be accomplished with fifty percent reduction in staffing and time compared to actual planned levels[18]. *"For JSF developments, simulations have improved the mechanical tolerances where the originally projected shim stock weight of 40 lbs per aircraft, as in the F-16, was reduced to less than 1 pound.*[19] " Cost was considered to be a major criteria during JSF requirement analysis phase. It was used as criteria for trade-studies. JSF is developed based on the simulation and acquisition program concept and collaborative engineering. Simulation was extensively used during the requirements development process, and will be used throughout the program. Virtual prototyping and collaborative engineering was used to integrate all stakeholders into the systems engineering process. Analysis provides the incremental approach for complete system definition, design and integration.

PART II: ALS Functional Analysis and Decompositions within AIM

The life support system provides for crew the necessary resources for activities such as food, water and waste management. Figures 12 and13 illustrate the level of interface between the crew, life support sub-systems and the four main sub-systems interaction of ALS.

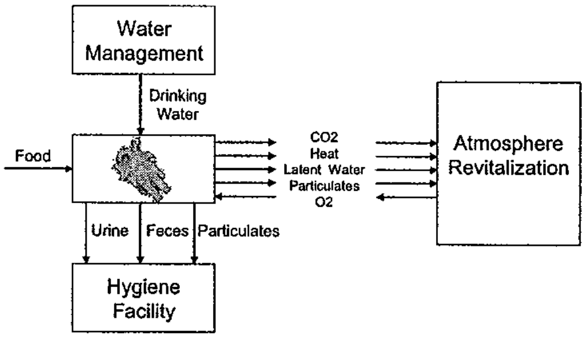


Figure 12. Crew and the Life Support System Interface[20]

A three phase methodology was proposed to further identify and decompose the life support functions. The steps within the methodology are:

1. Understand the System
    - Collect Information about the problem

---

[18] Boeing.com/defense-space/military/jsf/lean_mfg.html

[19] Building A Business Case for M&S, Acquisition Review Quarterly—Fall 2000

[20] D. Henninger, *"Lunar Base Life Support and Crew Health,"* Lunar Base Handbook , McGrawHill, 1999.

   - Organize the Requirements
   - Develop the Theme
2. Define Function
   - Select requirement for functional analysis
   - Define Functions
   - Define function criteria
3. Decompose and Systematize Functions
   - Identify main functions
   - Relate functions
   - Check functions series
   - Establish criteria

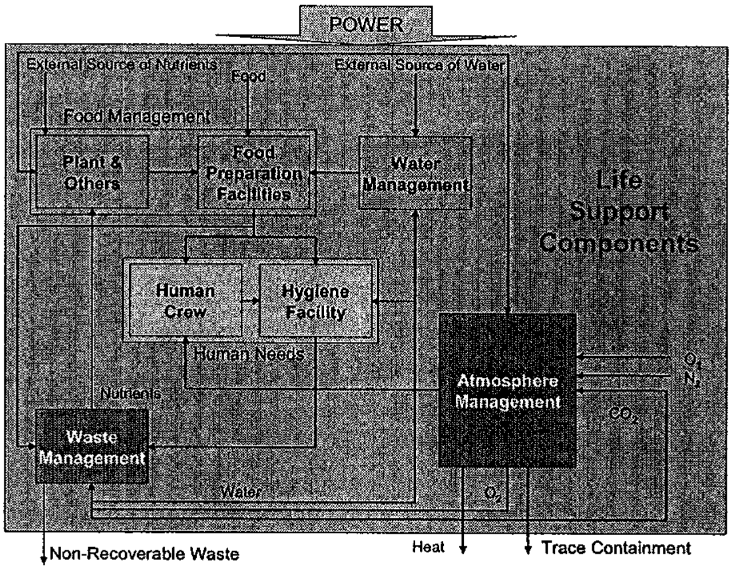


Figure 13. Life Support Sub-Systems[21]

To define the scope of the life support system, the affinity diagram was used to collected data from the team members. Affinity analysis is a process used to gather large amounts of data based on opinions, concepts and issues and then organizes them into sets of groups using their natural relationship. The Affinity process uses brainstorming sessions to generate and collect group ideas. Steps for developing the affinity diagram are:

1) Identify the problem
2) Generate ideas
3) Display ideas
4) Sort ideas into groups
5) Create header cards

---

[21] S. Doll, *"Life Support Functions and Technology Analysis for Future Missions,"* Proceeding of 20th Intersociety Conference on Environmental Systems, SAE Technical Paper901216, 1990.

6) Draw clustered groups and finished diagram

The issue of ***"How to Support Crew Life Beyond LEO?"*** was used to collect data from the team. The team included engineers, systems engineers and managers from both NASA and Lockheed. Figure 14 illustrate the results in the affinity diagram format.

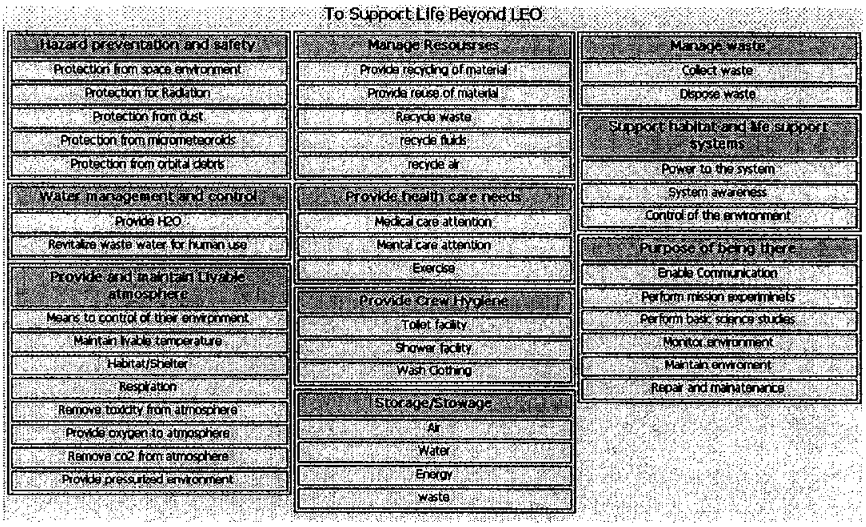


Figure 14. Result of the Affinity Analysis

Defining the functions of a given system involves asking the question of "**What is it action?**" Functions are typically expressed using the verbal model that combines a verb and a noun. Typically function is characterized by the degree to which it performance is required and fulfilled under certain condition. These are called criteria for functions; (e.g. mile/gallon). The criteria for functions are determined using the so-called 5W1H questions; what, who, when, where, why and how much. After further analysis of the affinity data and its interpretation to the requirements, the following partial functional requirements for ALS were identified:

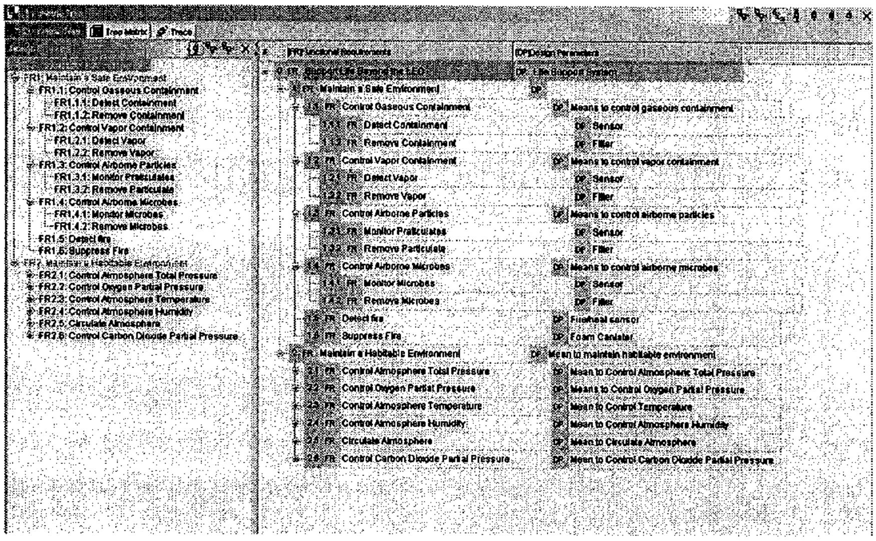
- Maintain a safe, habitable and operational environment.
- Provide resources for atmosphere, maintenance, crew consumption, and crew hygiene.
- Manage wastes for resource recovery.

Axiomatic design was used for further decomposition, systemization and mapping of the technologies. Axiomatic design provides the scientific basis and structure design approach to design identification, decomposition and mapping[22]. AD is a structured approach that associates the needs, requirements and solutions for system design problem. In Axiomatic Design approach, the customer wants is processes in such a way

---

[22] Num Suh,, "*The Principles of Design*," New York: Oxford University Press, 1990.

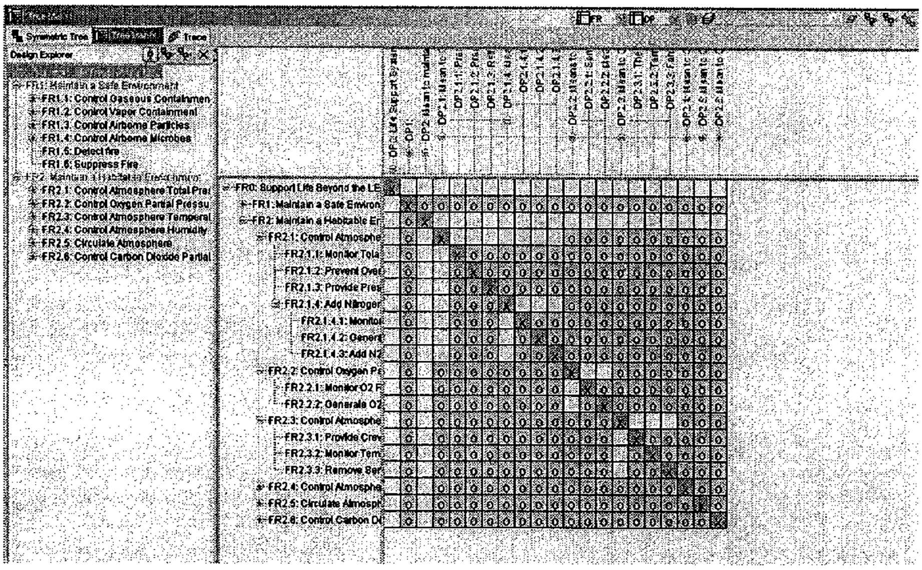
that lead to the definition of the functional requirements (FRs) which then identifies the design parameters (DPs). The FRs identify *what* needs to be done and DPs identify *how* each FR is implemented. Each DP is decomposed into lower level of FRs through zigzagging for further identifications of DPs and FRs[23]. This decomposition process continues until the DPs explain the design; design is complete. Axiomatic design was used functional requirements analysis of ALS. Sample results for decomposition and traceability chart is listed in Figures 15 and 16.



FR1: Maintain a Safe Environment
  FR1.1: Control Gaseous Containment
    FR1.1.1: Detect Containment
    FR1.1.2: Remove Containment
  FR1.2: Control Vapor Containment
    FR1.2.1: Detect Vapor
    FR1.2.2: Remove Vapor
  FR1.3: Control Airborne Particles
    FR1.3.1: Monitor Pralticulates
    FR1.3.2: Remove Particulate
  FR1.4: Control Airborne Microbes
    FR1.4.1: Monitor Microbes
    FR1.4.2: Remove Microbes
  FR1.5: Detect fire
  FR1.6: Suppress Fire
FR2: Maintain a Habitable Environment
  FR2.1: Control Atmosphere Total Pressure
  FR2.2: Control Oxygen Partial Pressure
  FR2.3: Control Atmosphere Temperature
  FR2.4: Control Atmosphere Humidity
  FR2.5: Circulate Atmosphere
  FR2.6: Control Carbon Dioxide Partial Pressure

FR/Functional Requirements	DP/Design Parameters
0 FR Support Life Beyond the LEO	DP Life Support System
1 FR Maintain a Safe Environment	DP
1.1 FR Control Gaseous Containment	DP Means to control gaseous containment
1.1.1 FR Detect Containment	DP Sensor
1.1.2 FR Remove Containment	DP Filter
1.2 FR Control Vapor Containment	DP Means to control vapor containment
1.2.1 FR Detect Vapor	DP Sensor
1.2.2 FR Remove Vapor	DP Filter
1.3 FR Control Airborne Particles	DP Means to control airborne particles
1.3.1 FR Monitor Pralticulates	DP Sensor
1.3.2 FR Remove Particulate	DP Filter
1.4 FR Control Airborne Microbes	DP Means to control airborne microbes
1.4.1 FR Monitor Microbes	DP Sensor
1.4.2 FR Remove Microbes	DP Filter
1.5 FR Detect fire	DP Firehead sensor
1.6 FR Suppress Fire	DP Foam Canister
2 FR Maintain a Habitable Environment	DP Mean to maintain habitable environment
2.1 FR Control Atmosphere Total Pressure	DP Mean to Control Atmospheric Total Pressure
2.2 FR Control Oxygen Partial Pressure	DP Means to Control Oxygen Partial Pressure
2.3 FR Control Atmosphere Temperature	DP Mean to Control Temperature
2.4 FR Control Atmosphere Humidity	DP Mean to Control Atmosphere Humidity
2.5 FR Circulate Atmosphere	DP Mean to Circulate Atmosphere
2.6 FR Control Carbon Dioxide Partial Pressure	DP Mean to Control Carbon Dioxide Partial Pressure

Figure 15. Partial listings of the ALS Decomposed functions



FR1: Maintain a Safe Environment
  FR1.1: Control Gaseous Containmen
  FR1.2: Control Vapor Containment
  FR1.3: Control Airborne Particles
  FR1.4: Control Airborne Microbes
  FR1.5: Detect fire
  FR1.6: Suppress Fire
FR2: Maintain a Habitable Environment
  FR2.1: Control Atmosphere Total Pre
  FR2.2: Control Oxygen Partial Pressu
  FR2.3: Control Atmosphere Temperat
  FR2.4: Control Atmosphere Humidity
  FR2.5: Circulate Atmosphere
  FR2.6: Control Carbon Dioxide Partial

	DP0: Life Support Sy	DP1:	DP2: Mean to mainta	DP2.1: Mean to	DP2.1.1: Pre	DP2.1.2: Pre	DP2.1.3: Ref	DP2.1.4: Ma	DP2.1.4.1	DP2.1.4.2	DP2.1.4.3	DP2.2: Mean to	DP2.2.1: San	DP2.2.2: Ele	DP2.3: Mean to	DP2.3.1: The	DP2.3.2: Tem	DP2.3.3: Fan	DP2.4: Mean to	DP2.5: Mean to	DP2.6: Mean to
FR0: Support Life Beyond the LE	X																				
FR1: Maintain a Safe Environ		X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2: Maintain a Habitable Er		O	X																		
FR2.1: Control Atmosphe		O		X								O	O	O	O	O	O	O	O	O	O
FR2.1.1: Monitor Tota		O			X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.1.2: Prevent Over		O			O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.1.3: Provide Pres		O			O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.1.4: Add Nitroger		O			O	O	O	X				O	O	O	O	O	O	O	O	O	O
FR2.1.4.1: Monitor		O			O	O	O		X	O	O	O	O	O	O	O	O	O	O	O	O
FR2.1.4.2: Generi		O			O	O	O		O	X	O	O	O	O	O	O	O	O	O	O	O
FR2.1.4.3: Add N2		O			O	O	O		O	O	X	O	O	O	O	O	O	O	O	O	O
FR2.2: Control Oxygen Pa		O		O	O	O	O	O	O	O	O	X			O	O	O	O	O	O	O
FR2.2.1: Monitor O2 F		O		O	O	O	O	O	O	O	O		X	O	O	O	O	O	O	O	O
FR2.2.2: Generate O2		O		O	O	O	O	O	O	O	O		O	X	O	O	O	O	O	O	O
FR2.3: Control Atmosphe		O		O	O	O	O	O	O	O	O	O	O	O	X				O	O	O
FR2.3.1: Provide Crev		O		O	O	O	O	O	O	O	O	O	O	O		X	O	O	O	O	O
FR2.3.2: Monitor Tem		O		O	O	O	O	O	O	O	O	O	O	O		O	X	O	O	O	O
FR2.3.3: Remove Ser		O		O	O	O	O	O	O	O	O	O	O	O		O	O	X	O	O	O
FR2.4: Control Atmosphe		O		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O
FR2.5: Circulate Atmospt		O		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O
FR2.6: Control Carbon Di		O		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X

Figure 16. Partial traceability matrix

---

[23] D. S. Cochran and A.K. Chu, *"Measuring Manufacturing System Design Effectiveness Based on the Manufacturing System Design Decomposition"*, 3rd World Congress on Intelligent Manufacturing Processes & Systems Cambridge, MA – June 28-30, 2000

CONCLUSION AND FUTURE PLANS

The mission of AIM is also to consider the HST technologies as an integral part of Advanced Life Support system development. The process focusing on the embodiment of technologies as part of the system's design is known as *technology-push*. This approach requires a new engineering paradigm that considers technology feasibility analysis and its integration into the customer-pull traditional SE process in order to validate the performance(s) of the technology within the overall system using parallel structure. Since no structured approach is available for the technology push method of design, potential risks of missing the mission needs and requirements are high. Despite these risks ***a successful process has significant benefits***. A new engineering paradigm is proposed[24] to consider perform this task. It will perform technology feasibility analysis and integrate it into the ALS SE development process in order to validate the performance(s) of the technology within the overall system using parallel structure. A step-by-step process is used to guide the systems engineer through testing and integration of the ALS technologies and then identifying corresponding HST design parameters. The three stages proposed for technology capability and feasibility analysis are ***1) Technology Evaluations, 2) Technology Opportunity Identification, and 3) Technology Mapping*** as shown in Figure 17.

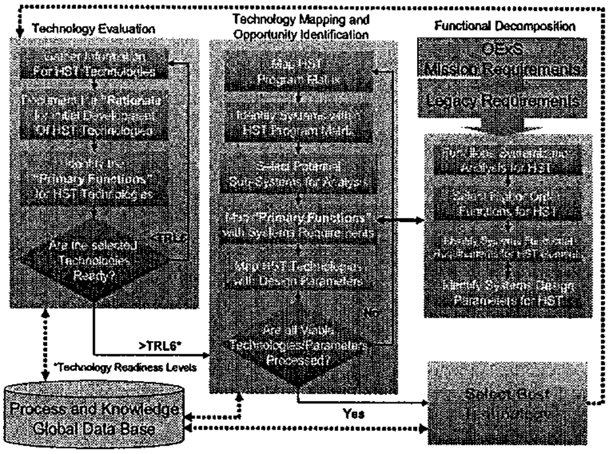


Figure 17. Integrated TP and SE Process for ALS and HST Mapping Methodology

Further research is necessary for the development and implementation of the proposed method. Potential sources of funding are being considered for the continuation.

---

[24] A. Kamrani, ALS Sub-Systems Design Integration & Testing within AIM, NFFP Directorate Proposal, (not funded), 2004.