# II. SYSTEMS ENGINEERING METHODOLOGY

## A. OVERVIEW

The conception, design, and manufacture of a complex system demands a disciplined process through which such a system transitions from an idea to a physical reality. Any system, whether it is complex or simple, can be defined as:

> "…an assemblage or combination of elements or parts forming a unitary whole, such as a river system or transportation system; any assemblage or set of correlated members, such as a system of currency; an ordered and comprehensive assemblage of facts, principles, or doctrines in a particular field of knowledge or thought, such as a system of philosophy; a coordinated body of methods or a complex scheme or plan of procedure, such as a system of organization and management; any regular or special method of plan of procedure, such as a system of marking, numbering, or measuring…" (Blanchard and Fabrycky, 1998, 1).

But systems are more than a group of components assembled to form a unitary whole. Systems, through the interaction of their elements, have "emergent properties" that arise only through the precise way in which their elements are combined. These "emergent properties" are greater than the sum of the individual capabilities of the elements; they define the system capabilities that either effectively or ineffectively meet the stakeholder's need. Indeed, systems are found in all realms and are analyzed and defined in all academic disciplines. The principles of Systems Engineering (SE) methodology, which govern the management, development, and manufacture of systems, can be applied in all fields. In particular we are interested in the management, development, and manufacture of technical, physical systems designed for military application.

A Systems Engineering and Analysis (SEA) team was organized through the Wayne E. Meyer Institute of Systems Engineering (WEMISE) at the Naval Postgraduate School (NPS) to conduct a study on the future of expeditionary warfare. An overarching SE methodology was crafted in order to guide the team through the process of engineering an architecture and overarching set of system requirements for a system of systems (SOS) to conduct expeditionary operations in littoral regions, exploring interfaces and system interactions, and comparing Current, Planned, and Conceptual architectures against these requirements. The mission of any SE methodology, according to the International Council on Systems Engineering (INCOSE), is to "assure the fully integrated development and realization of products which meet stakeholders' expectations with cost, schedule, and [performance] constraints" (INCOSE and American Institute of Aeronautics and Astronautics (AIAA), 1997, 3). The stakeholder, in this case, is the Deputy Chief of Naval Operations for Warfare Requirements and Programs, OPNAV N7 - the originator of the request for this study. The SE methodology provided a structured process for developing and integrating the overarching set of requirements and Conceptual architecture for the Integrated ExWar Project.

No two projects are completely alike. Applying a heuristic procedure to the development of an SE methodology implies that such a methodology must be tailored to the specific project to which it is to be applied. Tailoring an SE methodology to fit the needs of the project is perfectly acceptable provided the integrity of the process is maintained (INCOSE and AIAA, 1997, 4). For example, some projects, such as research and technology or the in-house studies of this kind, often only need to have the stakeholder requirements defined and validated with limited follow-up activities to ensure the integrity of requirements application (INCOSE and AIAA, 1997, 4).

The SEA team had undertaken The Integrated ExWar Project as an integrated team that included personnel from three different military services (Army, Navy, and Air Force), with a wide range of operational experiences, and different nationalities (Singapore and the United States). The SEA team concept strives to achieve the same synergies of talent that exist on DOD Integrated Product Process Development teams. Teams and similar collaborative efforts, as management experts Drs. Frank LaFasto and Carl Larson point out, are an excellent way to grapple with large complex problems (Lafasto and Larson, 2001, xix). Our team utilized an SE methodology to ensure the process was defined and adhered to by the team, to identify and resolve conflicts, and to verify that requirements developed by the team met stakeholder expectations (INCOSE and AIAA 1997, 4). As pointed out by INCOSE, "new and complex projects typically need robust Systems Engineering to succeed," but, "in all cases, the methods for applying the Systems Engineering process must be adapted to project and team needs" (INCOSE and AIAA, 1997, 4).

### 1. Definition of Systems Engineering

There is no commonly accepted definition of SE given that the field is still relatively new. Nevertheless, our preferred definition, which comes from the Defense Systems Management College (DSMC), is as follows:

> "The application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and (c) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into the total engineering effort to meet cost, schedule, supportability, and technical performance objectives. (DSMC, 1990, 12).

### 2. Definition of Systems Analysis

An essential technical activity supporting any Systems Engineering methodology is Systems Analysis (SA). Charles Calvano (Calvano, 2002a, 4), commented that according to the *Random House Dictionary of the English Language*, analysis is "the process of separation into components as a method of studying the nature of something or of determining its essential features and their relations". Therefore, SA, as it is utilized in SE, is the process of decomposing a system into its component parts for the purposes of study, evaluation, and/or generating requirements. At the conceptual stage, SA is often referred to "functional decomposition." When a conceptual system is decomposed into key functions it can be further analyzed and broken down into sub-functions until it is possible to describe and define various aspects of the conceptual system in greater detail. The information obtained from SA is then synthesized, i.e., the component functions and sub-functions are then reassembled into a more well-defined system set of requirements and the SE process is able to move forward. The process of decomposing systems into smaller parts and then synthesizing is illustrated graphically in Figure II-1.

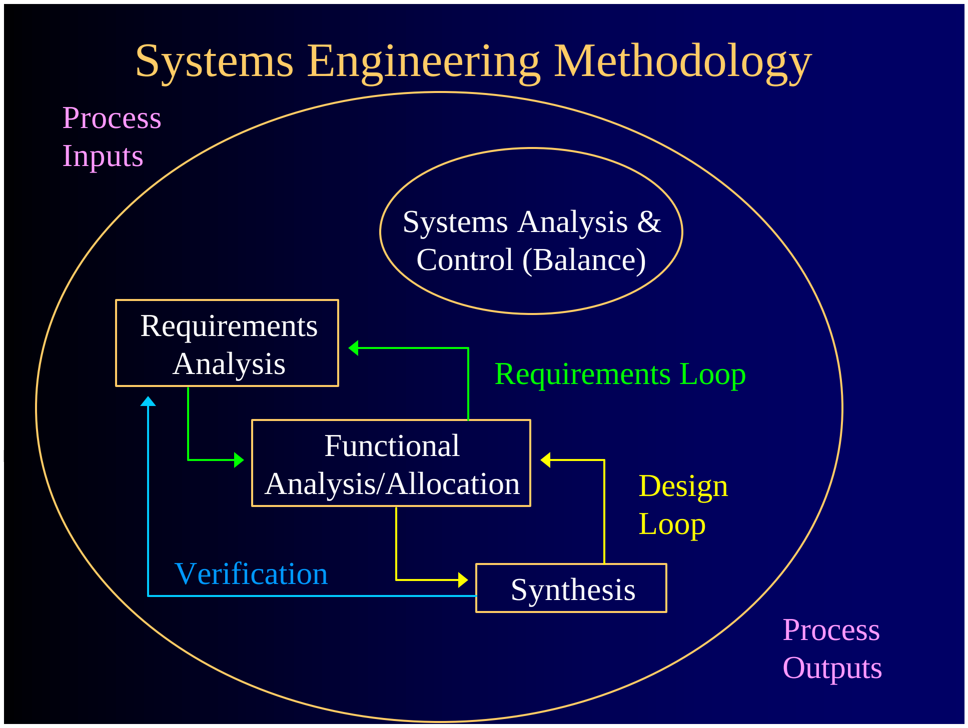


**Figure II-1**: Graphical Illustration of SE Methodology
(Source: MN 3331 School of Business, 2000, 4)

### 3. Top Down Analysis

SE methodology is based on a Top Down process that guides the engineer from mission need and concept definition to a design solution. The task of decomposing a conceptual system into its functional characteristics was described earlier in the definition of SA. Functional decomposition is the primary task of Top Down analysis.

As described by professors Blanchard and Fabrycky, there are two main characteristics of Top Down analysis. First, the process is applicable to the system as a whole or to any part of the system. Repeated application of this process will result in partitioning of the system into smaller and smaller functions until all that is left are the basic elements of the system. Second, "the process is self-consistent" (Blanchard and Fabrycky, 1998, 28). The properties of the system itself must be reproduced when the properties of smaller functions, sub-functions, and basic elements are synthesized to form the whole. A critical aspect of the Top Down process is that the systems engineer must "abstract from the particular case to the generic case, and represent the generic case by several interacting functional elements" (Blanchard and Fabrycky, 1998, 28). A particular functional element, identified through functional decomposition, can be associated with a whole class of systems. A class, in this case, is a set of systems that share a common structure and a common behavior; it comes into existence in order to help define problems and communicate solutions. Usually, only a few key functions are needed to represent a system assigned to a particular class. Identifying these functions is the basic starting point that allows the systems engineer to "engage in system design before physical manifestations have been defined" (Blanchard and Fabrycky, 1998, 28). Top Down analysis was incorporated into the SEA team's SE methodology within the context of an SOS approach. Top Down analysis enabled the SEA team to identify the functions associated with the component systems of the SOS.

#### 4. Bottom-Up Synthesis

The Top Down analysis of SE methodology contrasts sharply with Bottom Up synthesis where the integrator or design engineer "starts out with a defined set of real elements (systems in the case of an SOS) and synthesizes a system (or SOS) out of members from the set" (Blanchard and Fabrycky, 1998, 28). Traditional engineering design processes have relied on methods that employ Bottom-Up synthesis to create a product or system. The Bottom Up method of designing systems starting with known elements is iterative; often the functional need will not be met on the first attempt unless the system is simple. More complex systems require repeated attempts and "tweaks" in order for a Bottom Up approach to deliver a system capable of satisfying the stakeholder's need and operating within required performance parameters. Ultimately, a combination of system complexity and the designer's experience and creativity are what determine how many Bottom Up attempts are required to get the final product that's needed.

## B. SYSTEM OF SYSTEMS APPROACH

The initial objective of Integrated ExWar Project, according to OPNAV N7, was to "explore design concepts for future Expeditionary Warfare systems using a system of systems (SOS) approach" (McGinn, 2002, 1). Little exists in the way of a definition of a SOS. Our structural system definition described earlier includes elements, relationships, and emergent properties. The elements that comprise a SOS are individual systems. These systems, by definition, fulfill purposes in their own right and can continue to do so even if removed from the overall SOS. One way to describe the relationship among the individual systems within a SOS is each elemental system has managerial independence from the others (Calvano, 2002b, 6). In other words the elemental systems can be managed, at least in part, for their own purposes rather than the purposes of the whole SOS. The elemental systems are brought together only as needed. Another way to describe the relationship among the individual systems within an SOS is that each elemental system can, and often does, have geographical distribution (Calvano, 2002b, 6). Dispersion of elemental systems can be quite large and, as a result, physical linkages that would normally be necessary in individual systems are not necessary in an SOS. Information exchange between the elemental systems within an SOS can suffice as the defining linkage. An SOS performs functions that do not reside in any constituent system. Thus the emergent property or properties that, in part, define individual systems are present in an SOS (Calvano, 2002b, 7). Finally, a unique attribute of an SOS is that it is never fully formed or complete. The development of an SOS occurs over time; structure, function, and purpose are added, refined, or removed as circumstances change (Calvano, 2002b, 7). Scott Selberg of Agilent Technologies provides a more concise definition of an SOS, "A system of systems is a collection of independently useful systems which have been assembled to achieve further emergent properties" (Calvano, 2002b, 13).

The SEA team's task was to explore design concepts for expeditionary warfare using an SOS approach. The SEA team's SE methodology, therefore, had to account for the differences between a system and a SOS. Tables II-1 and II-2 show how SE principles, employed in the design of a military system, relate to the design a military SOS.

| SYSTEM | SYSTEM OF SYSTEMS |
|---|---|
| Configuration known in development | Configuration not known until time of use |
| Planned and budgeted for | Budget used for coordination and process definition |
| DOD organized to acquire | DOD not organized to acquire |
| Requirements state purpose of the system, not the purpose of the components | Requirements state the purpose of the system(s) and components |
| Program manager (PM) exists | PM role may not exist |
| Common objective through single management of resources | Common objective through consensus or compromise |

**Table II-1:** System Versus SOS Comparison Using DOD SE Principles
(Source: Calvano, 2002b)

| SE Principle | Level of Difficulty for SOS Application |
|---|---|
| Know problem, know customer | Medium |
| Establish and manage requirements | High |
| Identify, assess alternatives, and converge on a solution | Medium |
| Maintain system integrity | High |
| Manage to a plan | High |
| Verify and validate requirements and solution performance | High |

**Table II-2:** DOD SE Principles as Applied to an SOS
(Source: Calvano, 2002b)

A military SOS design solution must balance operational, technical, political, and economic considerations within cost, schedule, and performance constraints (Calvano, 2002b, 14). The SEA team's SE methodology, as applied to an SOS expeditionary warfare design solution, had to emphasize communication interfaces because in an SOS physical linkages are often not as important as the "soft" linkage of information exchange. In light of the SOS approach, the proper emphasis had to be placed on the understanding of key component systems because, unless these component systems' interfaces were effectively addressed and integrated, these systems would be unable or unwilling to interact (Calvano, 2002b, 17). The Integrated Expeditionary Warfare (ExWar) Project's SE methodology had to ensure that the SOS design solution requested by the stakeholder would not break down due to the failure to address the interfaces.

### 1. SE Methodology for an SOS Approach

According to professors Benjamin S. Blanchard and Wolter J. Fabrycky of the Virginia Polytechnic Institute and State University, there are two main differences between the Top Down and Bottom Up processes. First, with Top Down analysis, the "design process ends with the system elements as functional entities"—the realization of physical elements is not guaranteed whereas, in the case of Bottom Up synthesis, "physical realizability in terms of known elements is assured" (Blanchard and Fabrycky, 1998, 28). Second, "in the Top Down approach, the requirements are always satisfied through every step of the design process because it is an inherent part of the methodology, whereas in the Bottom Up approach the methodology provides no assurance that this will occur" (Blanchard and Fabrycky, 1998, 28). These important lessons provided sufficient reasons to combine the two approaches in the SEA team's SE methodology.

The Top Down analysis ensured that the SEA team was able to create a set of overarching requirements for an expeditionary warfare SOS. The Bottom Up synthesis provided the SEA team a process through which Current and Planned force structure architectures could be studied and compared to the overarching requirements identified in the Top Down analysis. The mismatches, or "holes," that were found as a result of the comparison of the two approaches were then translated into system-level *Initial Requirements Documents* that called on the Aerospace Design (Aero), TSSE, and Space Operations design teams to engineer system-level solutions for the Conceptual architecture. As Top Down analysis and Bottom Up synthesis occurred, feedback in the requirements and design loops (Fig. II-1) and verification of the requirements enabled the SEA team to update the overarching requirements document as necessary. Each phase of the SE process would bring another iteration of the "requirements loop." Furthermore, interaction between the SEA team and the design teams and academic groups across the NPS campus would bring still more feedback within the requirements and design loops and more updates to the overarching requirements. Quality controls, such as storyboards and electronic shared drives, were in place to ensure that all changes and updates to the SOS-level overarching requirements did not conflict with the derived need of the stakeholder. If traceability from the smallest component all the way up to the SOS derived need could not be achieved, errors would occur and quality could not be maintained. As the SEA team performed increasingly detailed analysis, new information was passed to the pertinent design teams and academic groups initiating new iterations in the "design loop."

## C. THE SYSTEMS ENGINEERING PROCESS

The SEA team developed an SE methodology that enabled it to undertake the Integrated ExWar Project and produce results that met the need of OPNAV N7. This methodology governed a process that was comprised of three phases: (a) Conceptual Design; (b) Preliminary Design; and (c) Detail Design and Development (Detail design, as used here, means design of the details of the concept and is not used in the traditional sense of producing production drawings and similar materials). The Integrated ExWar SE process is based on the SE process developed by Professors Blanchard and Fabrycky.

### 1. Conceptual Design, Phase 1A: Identify the Need

In any design development process one needs to ask basic questions like: "What products do we wish were available?; What is difficult with the current product we use?; and Why does it not do something we want it to?" (Otto and Wood, 2001, 17). The answers to these questions are visions for a new design; forming a vision helps the design team to analyze and understand what the stakeholder wants the new product to do. Although the task of identifying the need seems to be basic and obvious, "defining the problem is the most difficult part of the SE process" (Blanchard and Fabrycky, 1998, 46), and, as has been stated so many times, “all the serious mistakes are made in the first day” (Maier and Rechtin, 2002, 270). Getting this part right is of paramount importance.

The SEA team initiated this step upon receiving direction from the stakeholder in the form of a memorandum from Vice Admiral Dennis McGinn, Deputy Chief of Naval Operations for Warfare Requirements and Programs (OPNAV N7), dated 12 April 2002. Next the SEA team, conscious of the questions outlined above, conducted a focused study of germane Navy and Marine Corps operational concept papers and the Current and Planned force structure architectures for expeditionary warfare. The results of this study, and interaction with the Director, Expeditionary Warfare Division, N75, enabled the SEA team to derive and define the need that serves as the basis for the Integrated ExWar Project.

#### *a. Integrated ExWar Project Derived Need*

The Navy and Marine Corps need an ExWar Force that can accomplish Operational Maneuver From the Sea (OMFTS), (Headquarters, USMC, 1996), STOM, and Sea Basing through upgraded capabilities in the areas of amphibious lift, firepower, aviation support, Information Operations, force protection, Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR), and logistics.

### 2. Conceptual Design, Phase 1B: Management Plan

The next step in Phase 1 was to develop a management plan for the SE process. A management plan clearly defines exactly how the SE methodology will affect the overall project and translates the SE methodology into a plan of action and milestones. The following items describe the outcomes of the process of developing a management plan:

### *a. Define the Mission*

A mission provides the overall direction for the team to undertake a complex assignment in order to meet the need of the stakeholder. A clearly defined mission statement provided focus for the SEA team. It answered the question, “What is it we are trying to achieve?” when things got off track. Our mission statement is:

> To engineer an architecture and overarching set of system requirements for a system of systems to conduct expeditionary operations in littoral regions, exploring interfaces and system interactions, and comparing Current, Planned, and Conceptual architectures against these requirements.

### *b. Identify the Purpose and Then Scope the Problem*

It is not enough to define *what* is to be achieved without answering *why* it is to be achieved. The memorandum from the Deputy Chief of Naval Operations for Warfare Requirements and Programs dated 12 April 2002 clearly defined the purpose of the Integrated ExWar Project:

> “The value added is expected to be a better understanding of the interfaces and synergies among the ships, aircraft, and systems being developed now, along with the necessary *excursions* …”(OPNAV N7 2002, 1).

The scope of the project includes not only the mission, but any other outlying issues or excursions that are important to the stakeholder. The excursions mentioned by the stakeholder for the Integrated ExWar Project were: (1) High Speed Vehicle (HSV) types of high-speed platforms; (2) new Sea Basing options for logistics, command facilities, and support of sustained operations ashore; and (3) new options for the command and control of forces ashore (OPNAV N7, 2002, 1). Specific stakeholder interests pertaining to these excursions included: (1) the Effects of Speed of platforms on both logistics and warfighting; (2) the impact of a Reduced Footprint Ashore; (3) the possibilities for weapon and sensor Modularity and “missionizing” of ships; and (4) discovering opportunities for Reduced Manning of systems.

### c. *Assigning Responsibilities and Normalizing Organizational Behavior*

The specifics of team and design organization management and the allocation of responsibilities were all thoroughly discussed at the start of the SE process. Some had to be modified as circumstances changed. A team leader (U.S.) and deputy team leader (Singapore) for the SEA team were chosen. Meeting times and dates were established, and expectations for quality of work and division of labor were defined. A decision-making process involving group consensus was implemented. If consensus could not be achieved, majority rule would be invoked. Initially the team worked together to get preliminary aspects of the project accomplished. Sometimes, however, ad-hoc teams were formed to accomplish special, short-term missions such as writing an initial Concept of Operations (CONOPS) for the Conceptual architecture and *Initial Requirements Documents* (IRD) for the design teams. Eventually, as the project work grew more complex, permanent sub-teams with sub-team leaders were established to accomplish analysis and modeling. The SEA team leader interfaced with the other design team leaders; informal agreements were drawn up to govern the relationship between the SEA team, subsidiary design teams, and academic groups that were participating in the Integrated ExWar Project. Three faculty advisors - an academic advisor, a technical advisor, and a project advisor - were appointed to oversee various aspects of the team's efforts and ensure the overall project moved forward.

### d. *Choose the Tools*

Section 1, Chapter III of this report identifies the tools that were used to accomplish this project. The Functional Flow Block Diagram (FFBD) and Integrated Definition Language (IDEF) tools were the central tools used for requirements analysis. Various Operations Analysis techniques and the EXTEND™ modeling software were the major tools used later on in the project for architecting and evaluation. Many of the tools mentioned in Section 1, Chapter III were expensive to acquire, time consuming to learn and operate, and required a lot of lead-time to obtain. It is a good rule of thumb to carefully consider which tools will be used well in advance because of their critical importance to the successful outcome of the project.

### *e. Develop a Plan of Action and Milestones*

By identifying the ultimate deadline (the NPS graduation date for the team), the SEA team worked its way backward and chose sensible milestone dates for critical areas of the project. The overall plan of action and milestones then drove a more detailed schedule that governed specific pieces of the project. The detailed schedule often had to be modified as circumstances changed. Figure II-2 illustrates the overarching plan of action and milestones.

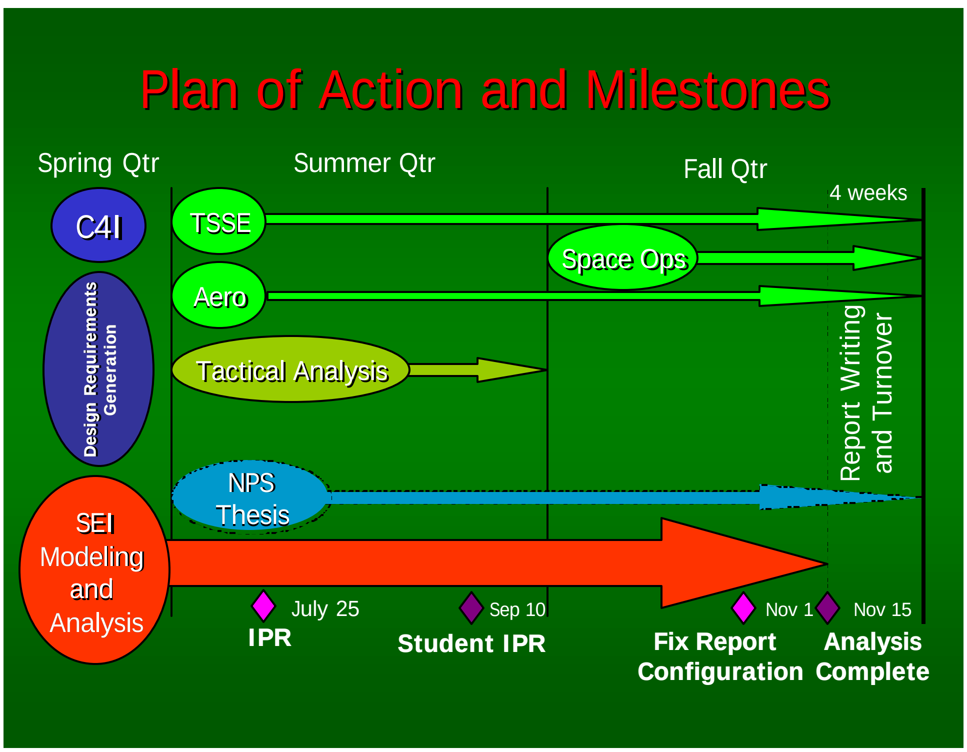


**Figure II-2:** Plan of Action and Milestones
(Source: SEA Team, 2002, 7)

### 3. Conceptual Design, Phase 1C: Defining the Capabilities Required

According to Professors Blanchard and Fabrycky, a requirement describes "the 'whats' not the 'hows' in terms of specific hardware, software, facilities, people, data, etc. The resources supporting the 'hows' will ultimately evolve from the functional analysis and allocation process. The "requirements must be complete and fully describe the user's need" (Blanchard and Fabrycky 1998, 49). Derek Hatley, a requirements engineer, explains further that, "system requirements are a technology-independent model of the problem the system is to solve" (Hatley, Hruschka, and Pirbhai, 2000, 49). In order for the SEA team to develop a Conceptual architecture as a design solution for expeditionary warfare, a thorough requirements analysis had to take place.

Requirements analysis starts with a need and ends with an initial definition of a system in functional terms. This process is iterative. Requirements analysis was repeated again and again until a clearly defined architecture emerged with performance specifications that enabled physical components to be designed and built. Requirements analysis occurred during every phase of the SE process. In the Conceptual Development Phase, requirements analysis produced the overarching SOS-level requirements that became the starting point for further functional decomposition and analysis in the next phase.

Before commencing functional decomposition, SA methods were employed in order to broaden the SEA team's understanding of the context in which an expeditionary warfare SOS might operate. The analysis sub-team within the SEA team undertook a thorough review of the hierarchy of governing documents describing expeditionary warfare. A threat analysis was conducted in order to predict and define the environment in which the ExWar Force would operate. Scenarios were developed in order to describe the types of operations the ExWar Force would be expected to undertake given the operational concepts and emerging threats. The SEA team, working with a Joint Campaign Analysis class in the Operations Research Department at NPS, developed more detailed operational timelines that would impact the ExWar Force. In addition, the SEA team developed a Concept of Operations for the Integrated ExWar Project that derived a set of high-level functions and implied capabilities for the ExWar Force. These are all further described in Section II, Chapters IV–VII.

Finally, the SEA team as whole began the daunting task of functional decomposition of the expeditionary warfare SOS. Functional Flow Block Diagram (FFBD) and Integrated Definition Language (IDEF) techniques, described further in Section 1, Chapter III, were used in order to develop an initial overarching set of SOS-level requirements. The actual overarching requirements are described further in Section 2, Chapter VIII.

#### 4. Preliminary Design, Phase 2A: Identifying the Capabilities Available

Most of the Bottom Up work done on the Current and Planned architectures occurred during this phase. For more information on the Current and Planned architectures, read Section 3, Chapters IX and X. The SEA analysis sub-team explored the capabilities of the ships, aircraft, weapons, and transportation devices employed in these force structures. The next step was to identify mismatches, or "holes," between the capabilities that were available, or would be available assuming the planned programs were fielded, and the capabilities that were required according to the Integrated ExWar Project's CONOPS and overarching SOS requirements document. Certain holes were then translated into Initial Requirements Documents (IRD) that were passed on to design teams like TSSE, Aero, and Space Systems so system-level platforms could be designed to fill these holes. The word *initial* was used in order to stress the tentative nature of these requirements documents. Indeed, further iteration and interaction between teams occurred in order to refine these design concepts. The design teams employed self-tailored SE methodologies at the systems level in order to accomplish their assigned tasks. From the point of view of the design teams, the SEA team was the stakeholder.

#### 5. Preliminary Design, Phase 2B: Developing the Conceptual Architecture

"The system architecture model is a technology-dependent model of the solution to the problem: It represents the 'how'" (Hatley, Hruschka, and Pirbhai, 2000, 49), and it describes the physical structure of the system or SOS. Systems architecting requires a great deal of creativity and artistic skill. Since every project is essentially different, there are no pre-determined mathematical formulas that can be used to precisely predict the right architectural solution to the problem. The SEA team's architecting procedure combined heuristics, modeling, and interactions with the design teams and other academic groups on the NPS campus. The overall process of architecting yielded more requirements updates—reemphasizing the iterative nature of the overall SE methodology and process illustrated in Figure II-1. In fact, as a well-known systems architect, Dr. Eberhardt Rechtin points out, "Systems requirements are an output of architecting, not really an input" (Maier and Rechtin, 2002, 18). While this runs contrary to the accepted convention, it is often the case that final requirements do not emerge until systems architecting has run its course. It is in this phase the Top Down analysis and Bottom Up synthesis converged as illustrated in Figure II-3.

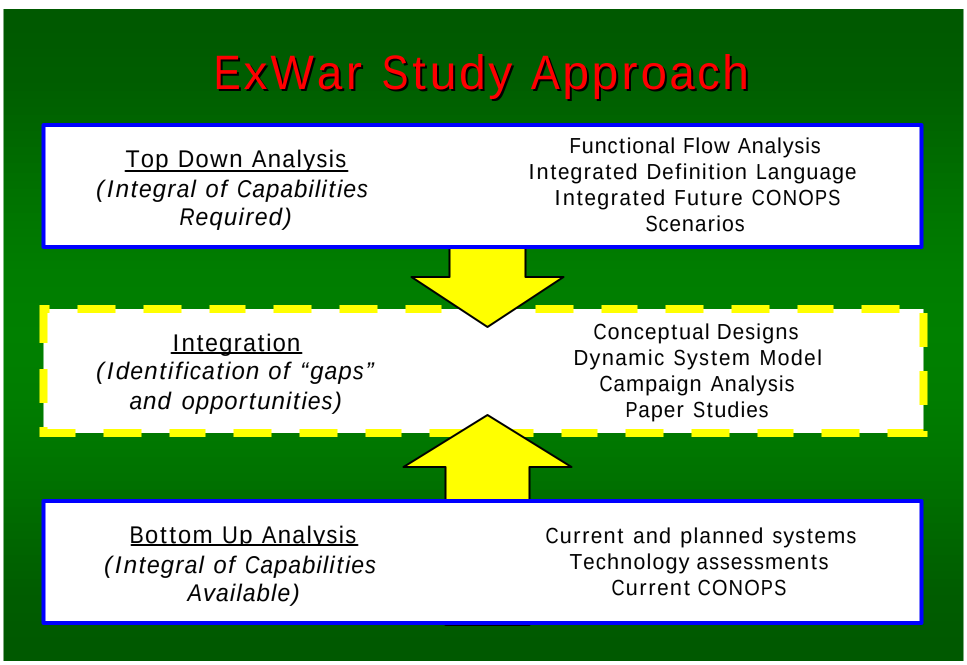


**Figure II-3:** Integrating the Two SA Approaches
(Source: SEA Team, 2002, 6)

### *a. Heuristics*

According to Dr. Rechtin, a heuristic is “a guideline for architecting, engineering, or design - a natural language abstraction of experience” (Maier and Rechtin, 2002, 294). “The art in architecting lies not in the wisdom of the heuristics, but in the wisdom of knowing which heuristics apply, a priori, to the current project” (Maier and Rechtin, 2002, 27). Here are some heuristics that applied to this project and SOS architecture:

<u>Multitask Heuristics</u>: (1) If anything can go wrong, it will (Maier and Rechtin, 2002, 269). (2) The first line of defense against complexity is simplicity of design (Maier and Rechtin, 2002, 269). (3) Don’t confuse the functioning of the parts for functioning of the system (Maier and Rechtin, 2002, 269).

<u>Scoping and Planning</u>: (1) Success is defined by the beholder, not by the architect (Maier and Rechtin, 2002, 270). (2) No complex system can be optimum to all parties concerned, nor all functions optimized (Maier and Rechtin, 2002, 270). (3) Don’t assume that the original statement of the problem is the best or even the right one (Maier and Rechtin, 2002, 271).

<u>Modeling</u>: (1) Modeling is a craft and at times an art (Maier and Rechtin, 2002, 272). (2) A model is not reality (Maier and Rechtin, 2002, 272). (3) Regarding intuition, trust but verify (Maier and Rechtin, 2002, 273). (4) If you can’t explain it in five minutes, either you don’t understand it or it doesn’t work (Maier and Rechtin, 2002, 273).

<u>Partitioning</u>: (1) Do not slice through regions where high rates of information exchange are required (Maier and Rechtin, 2002, 274). (2) Design the structure with “good bones” (Maier and Rechtin, 2002, 274).

<u>Integrating</u>: (1) When confronted with a particularly difficult interface, try changing its characterization (Maier and Rechtin, 2002, 275).

Assessing Performance: (1) A good design has benefits in more than one area (Maier and Rechtin, 2002, 276). (2) If you think your design is perfect, it's only because you haven't shown it to someone else (Maier and Rechtin, 2002, 276). The first quick-look analyses are often wrong (Maier and Rechtin, 2002, 277).

#### *b. Modeling*

Modeling is the creation of abstractions or representations of the system or SOS. Models are used to predict and analyze performance as well as serve as a means of communication in describing how the requirements will be achieved. During architectural development, paper modeling was used to develop and communicate concepts for the SOS architecture. The early use of EXTEND™ involved this type of modeling. Later on, as the model became more and more concrete and specific, EXTEND™ was used to perform an evaluation of the Current, Planned and Conceptual architectures. Other types of modeling tools used in architecting, such as ARENA™, EINSTein, and EXCEL, fleshed out smaller pieces of the SOS Conceptual architecture by analyzing sub-functions and recommending design solutions for the overall SOS Conceptual architecture. For more information on models, see Section 1, Chapter III.

#### *c. Interaction with Design Teams*

Interaction with the TSSE, Aero, and Space Operations design teams, as well as the C4ISR and Joint Campaign Analysis classes, was critical to architecting a conceptual force structure for the Integrated ExWar Project. The design teams provided physical platforms that were integrated into the overall architectural structure. Control of this integration process was done via requirements management. As trade-off studies and system level analyses of alternatives were conducted, the interfaces between heavy-lift aircraft and sea base capabilities were identified and the requirements for both platforms were updated to ensure the two systems were interoperable. The same held true for the design interfaces between the C4ISR architecture and the Space Operations conceptual design for a low-Earth orbit satellite described in greater detail in Section 4, Chapter

XVII. There are countless other examples of critical interfaces being tracked and managed by the SEA team through requirements management. As the physical pieces of the SOS took their final forms under the influence of team interaction, the Conceptual architecture was further and further refined.

### 6. Detail Design and Development, Phase 3

With an Integrated CONOPS in hand and a Conceptual architecture beginning to take shape, the SEA team used SA, at a deeper level, to: (1) evaluate the Current, Planned, and Conceptual architectures; and (2) address the stakeholders' concerns regarding project excursions. The design teams also refined their platforms and finalized their conceptual designs as well. For more information on this year's work on conceptual designs as well as previous NPS work on conceptual designs related to this project, read Section 4, Chapters XIV – XVIII.

#### *a. Evaluation of Architectures*

The EXTEND™ model was the centerpiece of the evaluation of the Current, Planned, and Conceptual architectures. This evaluation effort was analogous to the analysis of alternatives usually undertaken in the DOD acquisition process at the conceptual level. The types of comparisons and the use of modeling to quantify the results are shown in Figure II-3. For more information of the results of this evaluation, read Section 3, Chapter XIII.

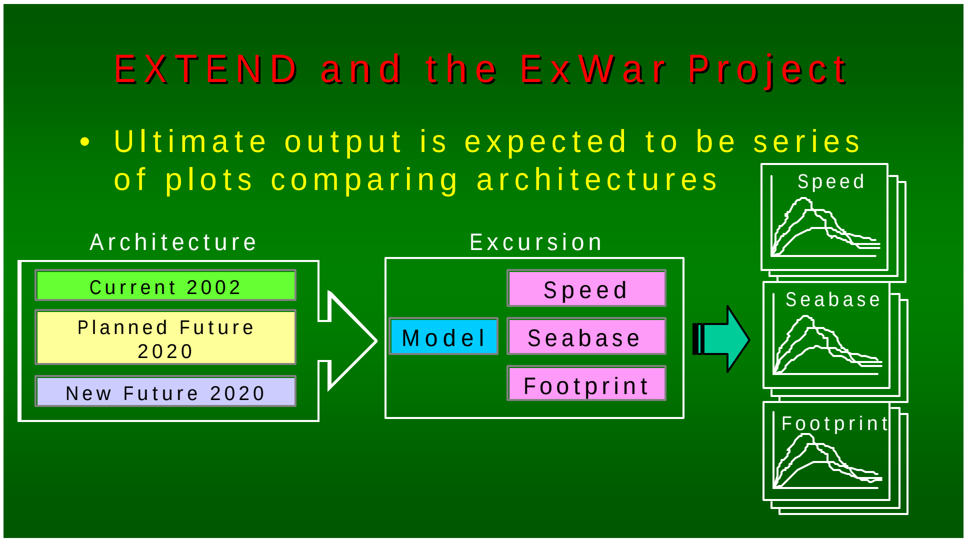


**Figure II-4:** Quantitative Process for Comparing the Current, Planned, and Conceptual Architectures (Source: SEA Team, 2002, 39)

### *b. Excursion Analysis*

The excursions, and their impacts, were evaluated for all three architectures and comparisons were made using modeling and other forms of analysis. For more information on the results of this comparison read Section 5, Chapters XIX–XXIII.

## D. SUMMARY

The Integrated ExWar Project used a well-defined, iterative SE methodology. This methodology combined a Top Down analysis and Bottom Up synthesis within the context of a system of systems approach. The SE methodology, in turn, governed a three-phase process by which a Conceptual architecture (ExWar Force) was developed and compared to two other alternatives (Current and Planned architectures). The Conceptual architecture, analysis of alternatives, and the impact of certain excursions fulfilled the need, mission, purpose, and scope of this project.