Systems Engineering Curriculum

Table of Contents

1.0 Introduction

This document is intended to provide useful guidance and information on systems engineering for engineering students. It provides a generic description of Systems Engineering (SE) as it should be applied throughout engineering design, implementation, testing, and operations. This document will increase awareness and consistency across engineering fields and advance the practice of SE. This document was adapted from the NASA Systems Engineering Handbook, published to bring the fundamental concepts and techniques of SE to NASA personnel in a way that recognized the nature of NASA systems and the NASA environment [1].

1.1 Scope

This document consists of three chapters: (1) an introduction, (2) a systems engineering fundamentals discussion, and (3) concepts of project life cycles. The chapters are supplemented by examples and additional information to illustrate topics in the chapters. The handbook makes use of charts and figures to define, refine, illustrate, and extend concepts in the chapters.

1.2 An Engineering Example

Throughout this document, a real-world engineering project example will be presented to clarify the SE concepts. In this project, a satellite will orbit the Earth. An imaging instrument will be mounted on the satellite, pointed towards the Earth. As the satellite orbits, the imaging instrument will collect data to detect fires on the Earth's surface.

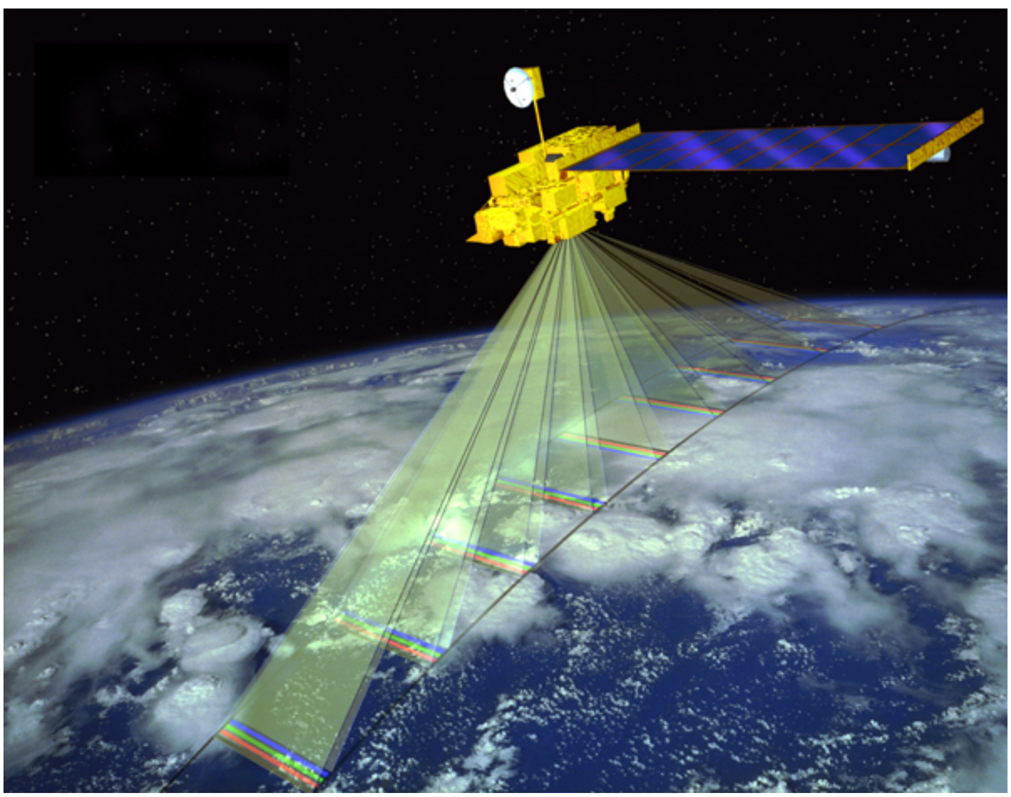

Figure 1 – Artist's Concept of the Terra Satellite - NASA

2.0 Fundamentals of Systems Engineering

Systems engineering is defined as a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and end-of-life retirement of a system. A *system* is the combination of elements that function together to produce the capability required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behavior, and performance. The value added by the system, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected.

> **Why Systems Engineering?**
>
> *It is the system's complexity, and severity of its constraints—not just its size—that drives the need for systems engineering… For large complex systems, there are literally millions of ways to fail to meet objectives, even after we have defined the 'right system.' It is crucial to work all the details completely and consistently and ensure that the designs and technical activities of all the people and organizations remain coordinated… Effective systems management requires applying a systematic, disciplined engineering approach that is quantifiable, recursive, repeatable, and demonstrable… Process definition and control are essential to effective, efficient, and consistent implementation.*
>
> \- The Art and Science of Systems Engineering [2]

A systems engineer is responsible for:

- Maintaining technical integrity throughout the complex system's lifecycle phases
- Guiding the end-to-end engineering of a design
- Ensuring the development and assessment of the concept options
- Ensuring all technical information is properly identified and archived, answering questions, and resolving issues as they arise

> **Two Sides of Systems Engineering**
>
> *Systems engineering is both an art and a science… Technical leadership, the art of systems engineering, balances broad technical domain knowledge, engineering instinct, problem solving, creativity, leadership, and communication to develop new missions and systems… Systems management is the science of systems engineering. Its focus is on rigorously and efficiently managing the development and operation of complex systems.*
>
> \- The Art and Science of Systems Engineering

2.1 The Common Technical Processes and the SE Engine

There are three sets of common technical processes related to Systems Engineering processes and requirements:

- System Design
- Product Realization
- Technical Management

The processes in each set and their interactions and flows are illustrated by a systems engineering "engine". The processes of the SE engine are used to develop and realize the end products. The application context consists of the 17 common technical processes. Processes 1 through 9 represent the tasks in the execution of a project. Processes 10 through 17 are crosscutting tools for carrying out the processes.

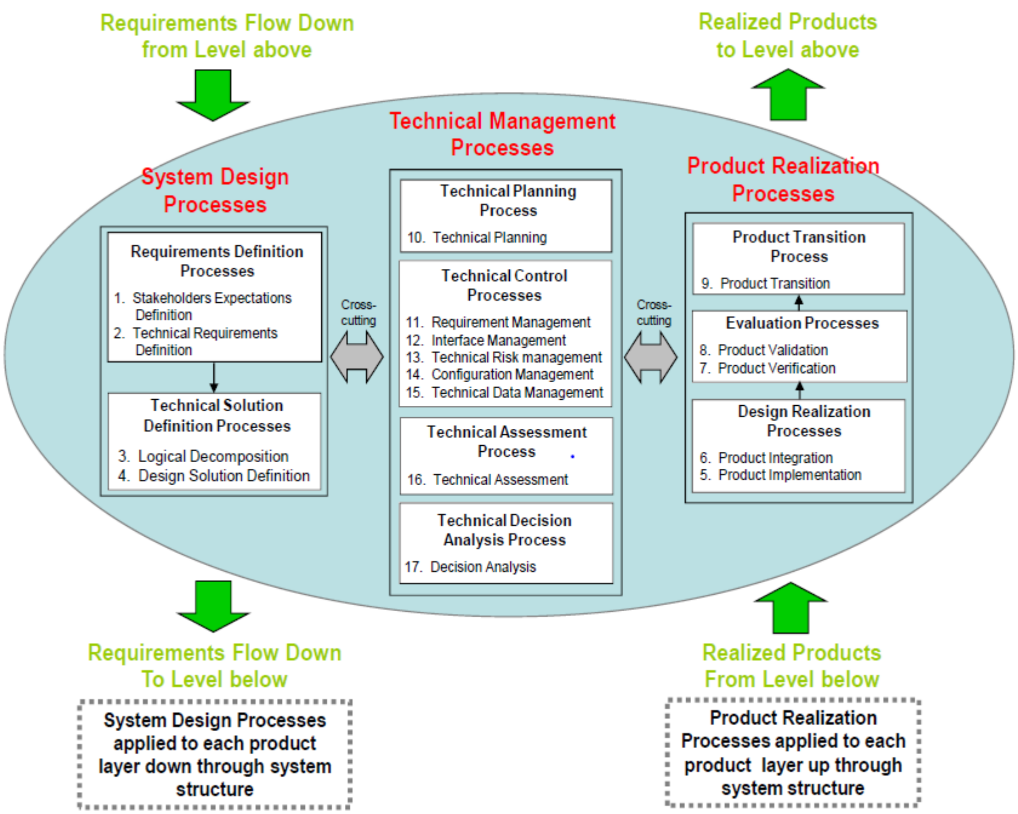

Figure 2 – System Engineering Engine

Student Activity:

- Identify the 3 sets of common technical processes
- Identify the various processes contained within each set of common technical processes
- Identify the interactions and flows between each set of common technical processes
- Identify the high-level goals of the operational system

2.2 An Overview of the SE Engine by Project Phase

The Systems Engineering engine is used during each phase of a project (Pre-Phase A through Phase F). The project phases allow reference to project system maturity, as the project progresses from a feasible concept to an as-deployed system; phase activities; Key Decision Points (KDPs); and major project reviews. Next, the technical development processes (steps 1 through 9) in each project phase are detailed.

The SE engine cycles five times from Pre-Phase A through Phase D.

Phase		Purpose	Typical Outcomes
Pre-Formulation	Pre-Phase A Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mockups
Formulation	Phase A Concept and Technology Development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with organization's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mockups, and trade study definition
	Phase B Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mockups, trade study results, specification and interface documents, and prototypes
Implementation	Phase C Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D System Assembly, Integration and Test, Launch	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it can meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products

Once a project enters into its operational state (Phase E) and closes out (Phase F), the technical work shifts to activities commensurate with these last two project phases. Then, the eight technical management processes (steps 10 through 17) in each project phase are commenced. The SE engine cycles the technical management processes seven times from Pre-Phase A through Phase F.

Phase		Purpose	Typical Outcomes
	Phase E Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

Student Activity:

- Identify the various phases of the project lifecycle
- Identify and construct deliverables for each phase of the project lifecycle

2.3 Example of Using the SE Engine

In Pre-Phase A, the SE engine is used to develop the initial concepts:

- Clearly define the unique roles of humans, hardware, and software in performing the project objectives; establish the system functional and performance boundaries
- Develop/identify a preliminary/draft set of key high-level requirements, define one or more initial Concept of Operations (ConOps) scenarios
- Realize these concepts through iterative modeling, mockups, simulation, or other means
- Verify and validate that these concepts and products would be able to meet the key high-level requirements and ConOps.

The operational concept must include scenarios for all significant operational situations, including known off-nominal situations. To develop a useful and complete set of scenarios, important malfunctions and degraded-mode operational situations must be considered. The importance of early ConOps development cannot be underestimated. As system requirements become more detailed and contain more complex technical information, it becomes harder for the stakeholders and users to understand what the requirements are conveying.

Example: Imaging Spectroradiometer Used for Fire Detection (Concept of Operations)

An imaging spectroradiometer is a light measurement tool which can measure the light emitted from a light source. Spectroradiometers are used in many applications, including LED measurement, the detection of oil slicks, solar ultraviolet radiation measurement and fire detection.

An example of an imaging spectroradiometer is shown in Figure 3 below:

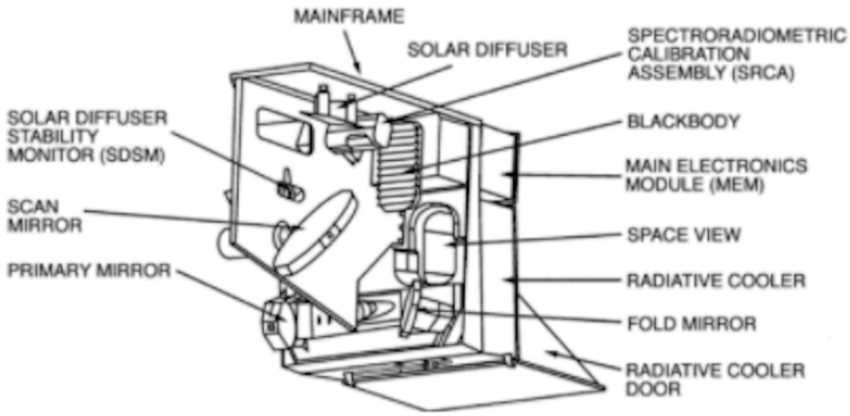

Figure 3 – The Moderate Resolution Imaging Spectroradiometer (MODIS)
Source: NASA Goddard Space Flight Center

For the planned concept, the imaging spectroradiometer is mounted on a spacecraft. As the spacecraft orbits the Earth, the imaging spectroradiometer measures and distributes data on light sources on the Earth's surface that are used to detect fires.

Some satellites that observe the Earth have a nearly polar orbit. These satellites move around the Earth from pole to pole, taking about 99 minutes to complete an orbit. During half of the orbit, the satellite views the daytime side of the Earth. At the pole, satellite crosses over to the nighttime side of Earth. As the satellites orbit, the Earth turns underneath. By the time the satellite crosses back into daylight, it is over the region adjacent to the area seen in its last orbit. In a 24-hour period, polar orbiting satellites will view most of the Earth twice: once in daylight and once in darkness. For the project, the imaging spectroradiometer would be mounted on a spacecraft operating in a polar orbit.

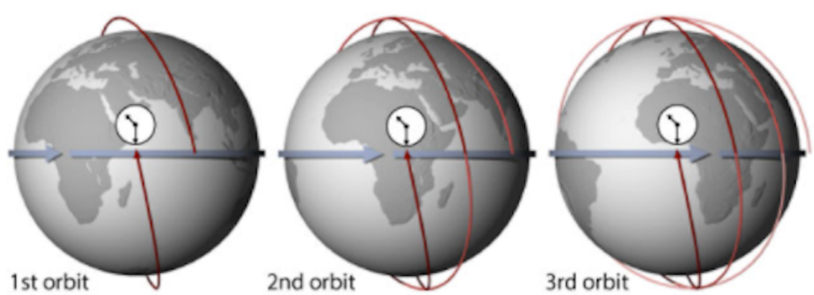

Figure 4 – Path of Satellite Orbiting Earth (Polar Orbit)

The ConOps can serve as a check in identifying missing or conflicting requirements. Note that this Pre-Phase A initial concepts development work is not the formal verification and validation program that is performed on the final product, but rather it is a methodical run through ensuring that the concepts that are being developed in this Pre-Phase A are able to meet the likely requirements and expectations of the stakeholders. Concepts are developed to the lowest level necessary to ensure that they are feasible and to a level that reduces the risk low enough to satisfy the project. Academically, this process could proceed down to the circuit board level for every system; however, that would involve a great deal of time and money.

During Phase A, the recursive use of the SE engine is continued, this time taking the concepts and draft key requirements that were developed and validated during Pre-Phase A and fleshing them out to become the set of baseline system requirements and ConOps. During this phase, key areas of high risk are documented to ensure that the concepts and requirements being developed are complete and to identify verification and validation tools and techniques needed in later phases.

Example: Imaging Spectroradiometer Used for Fire Detection (Requirements)

Based on the ConOps, at this phase, the initial requirements will be established:

Sample Requirements	
1.0	The imaging spectroradiometer shall have the ability to detect fires from Space
2.0	The imaging spectroradiometer shall be able to transfer spectroradiometer data to the spacecraft bus
3.0	The imaging spectroradiometer shall be able to measure imaging data during day or night from the Earth's surface
4.0	The imaging spectroradiometer measurement parameters shall be configurable

Student Activity:

Students will read the concept-related article: https://spectrum.ieee.org/how-the-boeing-737-max-disaster-looks-to-a-software-developer

Students will write a concept of operations based on an engineered subsystem (e.g., steering wheel in a car, light bulb in a refrigerator or camera in a cell phone). The concept of operations will explain how the subsystem fits within the larger engineered system. The students will also write 3 – 5 high level requirements for the subsystem.

During Phase B, the SE engine is applied recursively to further mature requirements and designs for all products in the developing product tree and perform verification and validation of concepts to ensure that the designs can meet their requirements. Operational designs and mission scenarios are evaluated and feasibility of execution within design capabilities and cost estimates are assessed.

Example: Imaging Spectroradiometer Used for Fire Detection (Design)

For this example, the mission scenario the imaging spectroradiometer is mounted on a spacecraft operating in a polar orbit. Additionally, the polar orbit will be in the low earth orbit (LEO), an Earth-centered orbit with an altitude of 1,200 mi (2,000 km) or less. As a result, the imaging spectroradiometer will need to be able to measure light on the Earth's surface, sufficient to detect a fire from 1,200 miles away.

Phase C again uses the left side of the SE engine to finalize all requirement updates, finalize the ConOps validation, develop the final designs to the lowest level of the product tree, and begin fabrication.

Phase D uses the right side of the SE engine to recursively perform the final implementation, integration, verification, and validation of the end-product, and at the final pass, transition the end product to the user.

Example: Imaging Spectroradiometer Used for Fire Detection (Implementation and V&V)

During Phase D, the imaging spectroradiometer will be built. Once built, the imaging spectroradiometer will be tested to verify that it meets the defined requirements. Once the requirements are verified, the imaging spectroradiometer will be integrated with the spacecraft. The spacecraft that hosts the imaging spectroradiometer will represent its operational environment. Once the imaging spectroradiometer is installed, it will be tested again to validate that it meets the defined requirements within an operational environment.

The technical management processes of the SE engine are used in Phases E and F to monitor performance; control configuration; and make decisions associated with the operations, sustaining engineering, and closeout of the system. Any new capabilities or upgrades of the existing system reenter the SE engine as new developments.

Example: Imaging Spectroradiometer Used for Fire Detection (Sustaining Engineering)

During Phase E, the imaging spectroradiometer will be operating in space and measuring light from the Earth's surface. Data from the imaging spectroradiometer will be transmitted to the spacecraft communications system. From the spacecraft, the data will be transmitted to resources on the Earth. The sustaining engineering elements in Phase E will include remote sensing and measurement, data transmission and system maintenance.

Student Activity:

Based on the previous student concept of operation, students will write 3 – 5 sustaining engineering actions for the subsystem.

2.4 The Systems Engineer's Dilemma

The objective of systems engineering is to see that the system is designed, built, and can be operated so that it accomplishes its purpose safely in the most cost-effective way possible considering performance, cost, schedule, and risk. A cost-effective and safe system should provide a particular kind of balance between effectiveness and cost. This causality is an indefinite one because there are usually many designs that meet the cost-effective condition.

Technical Risk

Risk is the potential for performance shortfalls, which may be realized in the future, with respect to achieving explicitly established and stated performance requirements. The performance shortfalls may be related to institutional support for project execution or related to any one or more of the following mission execution domains:

- safety
- technical
- cost
- schedule

Systems engineers are involved in this process to help identify potential technical risks, develop mitigation plans, monitor progress of the technical effort to determine if new risks arise or old risks can be retired, and to be available to answer questions and resolve issues.

Design trade studies (choosing between options available for an activity), an important part of the systems engineering process, often attempt to find designs that provide the best combination of cost and effectiveness. At times there are alternatives that either reduce costs without reducing effectiveness or increase effectiveness without increasing cost. In such "win-win" cases, the systems engineer's decision is easy. When the alternatives in a design trade study require trading cost for effectiveness, the decisions become harder.

The Systems Engineer's Dilemma

At each cost-effective solution:

- To reduce cost at constant risk, performance must be reduced.
- To reduce risk at constant cost, performance must be reduced.
- To reduce cost at constant performance, higher risks must be accepted.
- To reduce risk at constant performance, higher costs must be accepted.

In this context, time in the schedule is often a critical resource, so that schedule behaves like a kind of cost.

Figure 5 shows that the life-cycle costs of a program or project tend to get "locked in" early in design and development. The cost curves clearly show that late identification of and fixes to problems cost considerably more later in the life cycle. Conversely, descopes taken later versus earlier in the project life cycle result in reduced cost savings. This figure, obtained from the Defense Acquisition University, is an example of how these costs are determined by the early concepts and designs. The numbers will vary from project to project, but the general shape of the curves and the message they send will be similar. For example, Figure 5 shows that during design, only about 15% of the costs might be expended, but the design itself will commit about 75% of the life cycle costs. This is because the way the system is designed will determine how expensive it will be to test, manufacture, integrate, operate, and sustain. If these factors have not been considered during design, they pose significant cost risks later in the lifecycle. Also note that the cost to change the design increases as you get later in the life cycle. If the project waits until verification to do any type of test or analysis, any problems found will have a significant cost impact to redesign and reverify.

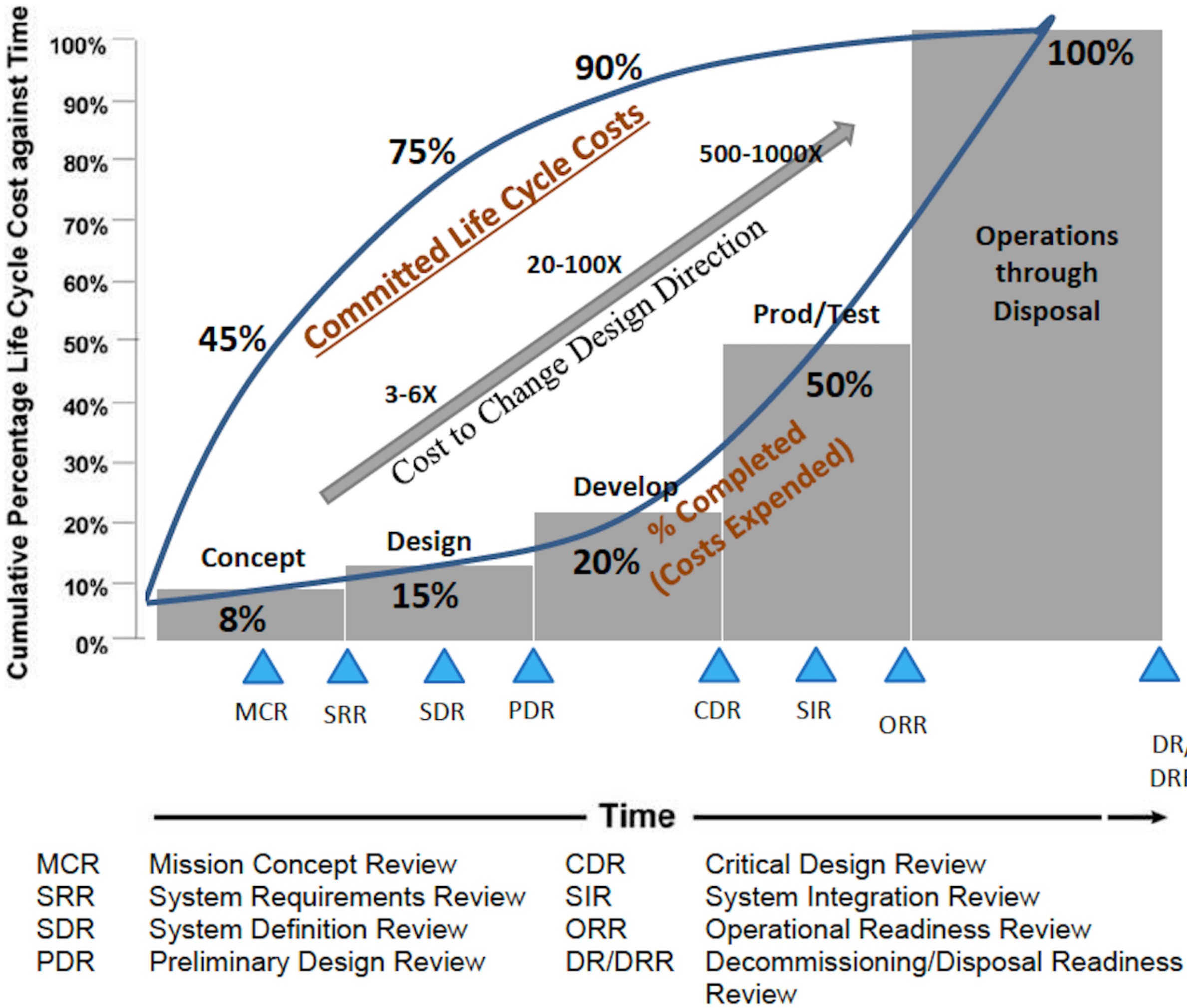

Figure 5 - Life-Cycle Cost Impacts from Early Phase Decision-Making
Adapted from INCOSE-TP-2003-002-04, 2015

The technical team may have to choose among designs that differ in terms of numerous attributes. A variety of methods have been developed to help uncover preferences between attributes and quantify subjective assessments of relative value. When this is done, trades between attributes can be assessed quantitatively. Often, however, the attributes are incompatible. In the end, decisions need to be made despite the given variety of attributes.

Example: Imaging Spectroradiometer Data Storage (Design Trade-offs)

An imaging spectroradiometer, will be hosted on a spacecraft operating in a low Earth polar orbit. The spacecraft will not have continuous access to Earth-based ground stations to collect data. The spacecraft will not always be in view of an applicable ground station. As a result, the imaging spectroradiometer will need the ability to store data, between transmission opportunities. However, when considering the design of the imaging spectroradiometer, the system weight, power and size of the storage device will be constrained by the limited operations specifications of the spacecraft. Based on these parameters, the storage design will need to consider the trade-offs between the size of the storage, based on spacecraft operational constraints, versus the risk of not collecting enough data to meet the mission objectives. Solutions that reduce the risk and meet the storage requirements will likely be expensive, due to the cost of a specialized miniaturized solution. As a result, cost will be a consideration in the design as well.

Student Activity:

Based on a selected concept of operations with an engineered subsystem (e.g., steering wheel in a car, light bulb in a refrigerator or camera in a cell phone), the concept of operations will explain how the subsystem fits within the larger engineered system. The students will identify trade-offs for the design of the subsystem, based on parameters such as cost, size, weight, capability.

3.0 Project Life Cycle

One of the fundamental concepts used for the management of major systems is the project life cycle, which categorizes all actions required to accomplish a project into distinct phases separated by Key Decision Points (KDPs). KDPs are the events at which the decision authority determines the readiness of a project to progress to the next phase of the life cycle (or to the next KDP). Phase boundaries are defined so that they provide natural points for “go” or “no-go” decisions. Decisions to proceed may be qualified by liens that should be removed within an agreed-to time period. A project that fails to pass a KDP may be allowed to try again later after addressing deficiencies that precluded passing the KDP, or it may be terminated.

All systems start with the recognition of a need or the discovery of an opportunity and proceed through various stages of development to the end of the project. While the most dramatic impacts of the analysis and optimization activities associated with systems engineering are obtained in the early stages, decisions that affect cost continue to be amenable to the systems approach even as the end of the system lifetime approaches. Decomposing the project life cycle into phases organizes the entire process into more manageable pieces. The project life cycle should provide managers with incremental visibility into the progress being made at points in time that fit with the management and budgetary environments.

The Phases of the Project Life Cycle

Program Pre-Formulation:

- Pre-Phase A: Concept Studies

Program Formulation

- Phase A: Concept and Technology Development
- Phase B: Preliminary Design and Technology Completion

Program Implementation:

- Phase C: Final Design and Fabrication
- Phase D: System Assembly, Integration and Test, Launch
- Phase E: Operations and Sustainment
- Phase F: Closeout

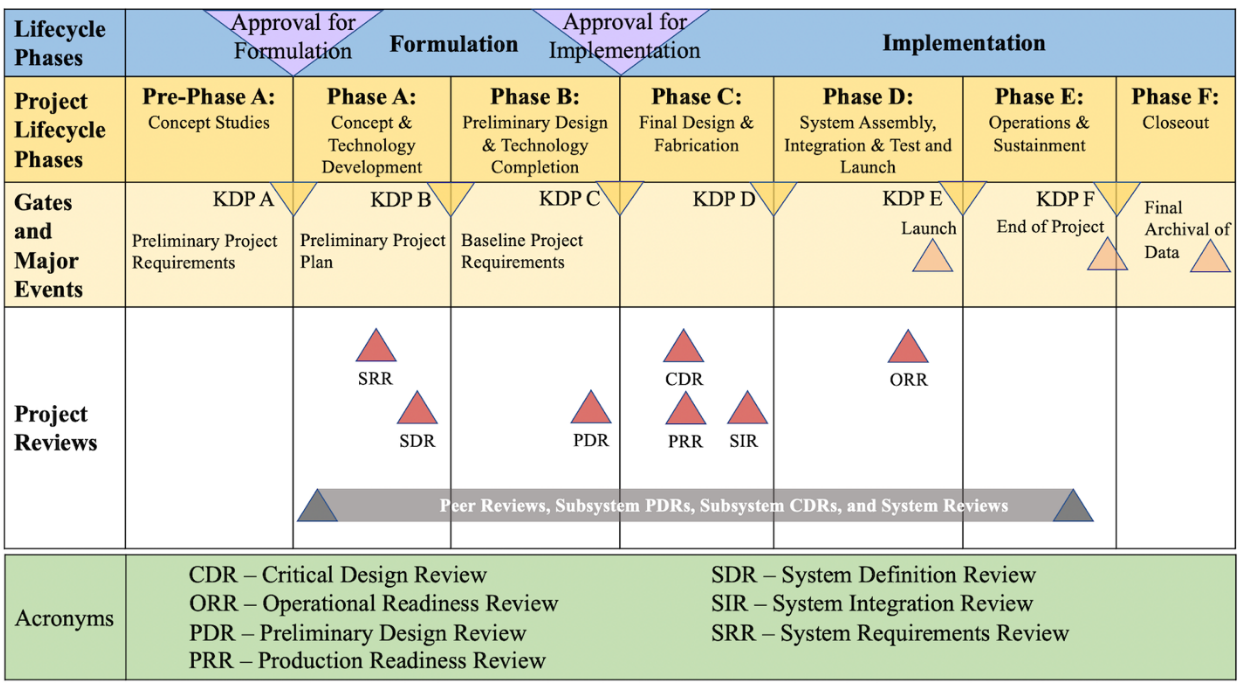

Figure 6 – Project Life Cycle

Technical Assessment

Technical assessment is the crosscutting process used to help monitor technical progress of a project through periodic technical reviews and through monitoring of technical indicators. The reviews and associated metrics also provide status information to support assessing system design, product realization, and technical management decisions.

3.1 Project Pre-Phase A: Concept Studies

The purpose of Pre-Phase A is to produce a broad spectrum of ideas and alternatives for a system design from which new projects can be selected. During Pre-Phase A, a project team analyzes a broad range of system design concepts that can fall within technical, cost, and schedule constraints and that contribute to project goals and objectives. Pre-Phase A effort could include focused examinations on high-risk or high technology development areas. These advanced studies, along with interactions with customers and other potential stakeholders, help the team to identify promising system design concept(s).

The key stakeholders (Including the customer) are determined and expectations for the project are gathered from them. If feasible concepts can be found, one or more may be selected to go into Phase A for further development.

Example: Imaging Spectroradiometer (Concept Studies)

> An imaging spectroradiometer is a light measurement tool which can measure the light emitted from a light source. However, in the *Concept Studies* phase of the project, the engineering team must consider multiple technologies. Since the goal of the project is to design, build and operate a sensor that detects and conveys the information necessary to detect fires, the engineering team will consider multiple sensing technologies.
>
> While some of the sensing technologies will be high risk, ultimately, the engineering team will select a technology that considers the technical capability, cost, and schedule constraints.

Typically, the system engineers are heavily involved in the development and assessment of the options available to bring the concept to fruition. Descope options define what the system can accomplish if the resources are not available to accomplish the entire project. This could be in the form of fewer instruments, a less ambitious system design profile, accomplishing fewer goals, or using cheaper, less capable technology. Descope options can also reflect what the system design can accomplish in case a hardware failure; for example, what a satellite can accomplish if a power solar panel fails.

The success criteria are reduced to correspond with a descoped project. In Pre-Phase A, the purpose is to determine feasibility of desired system; develop system design concepts; draft system-level requirements; assess performance, cost, and schedule feasibility; identify potential technology needs and scope.

Key Concepts in Risk Management

Risk is the potential for shortfalls, which may be realized in the future with respect to achieving explicitly stated requirements. The performance shortfalls may be related to institutional support for project execution or related to any one or more of the following mission execution domains: safety, technical, cost, schedule.

Risk is characterized as a set of triplets:

- The scenario(s) leading to degraded performance in one or more performance measures.
- The likelihood(s) of those scenarios.
- The consequence(s), impact, or severity of the impact on performance that would result if those scenarios were to occur.

When selecting the measured criteria or classification for risk, normalization can be used to establish a common base for mathematical operations. The process of "normalization" is making a scale so that all different kinds of criteria can be compared or added together. This can be done informally (e.g., low, medium, high), on a scale (e.g., 1-3-9), or more formally with a tool.

Student Activity:

Based on the previous student concept of operation, students will conduct the listed activities and produce the listed products for a Systems Concept Review (SCR):

- Review/identify any initial customer requirements or scope of work
- At a high-level, document what this system will deliver
- Identify and involve users and other stakeholders
    - Identify key stakeholders for each phase of the life cycle
    - Identify key stakeholders' roles and responsibilities
    - Capture and baseline expectations as Needs, Goals, and Objectives (NGOs)
    - Define measures of effectiveness
- Develop and baseline the Concept of Operations
    - Identify and perform tradeoffs and analyses of alternatives (AoA)
    - Perform preliminary evaluations of possible systems
- Identify initial technical risks
    - Identify risk classification (High, Medium, Low) for each technical risk
- Life-cycle rough order of magnitude (ROM) cost, schedule, and risk estimates

3.2 Project Phase A: Concept and Technology Development

The purpose of Phase A is to develop a proposed system architecture that is credible and responsive to program expectations, requirements, and constraints on the project, including resources. During Phase A, activities are performed to fully develop a baseline system design concept, begin the development of needed technologies, and clarify expected reliance on human elements to achieve full system functionality or autonomous system development. This work, along with interactions with stakeholders, helps mature the system design concept and the program requirements on the project. Systems engineers are heavily involved during this phase in the development and assessment of the architecture and the allocation of requirements to the architecture elements.

In Phase A, the team readdresses the system design concept first developed in Pre-Phase A to ensure that the project justification and practicality are sufficient and then focuses efforts on analyzing project requirements and establishing a system design architecture. Activities become formal, and the emphasis shifts toward optimizing the concept design. The effort addresses more depth and considers many alternatives. Goals and objectives are solidified, and the project develops more definition in the system requirements, top-level system architecture, and ConOps. Conceptual designs and analyses (including engineering units and physical models, as appropriate) are developed and exhibit more engineering detail than in Pre-Phase A. Technical risks are identified in more detail, and technology development needs become focused. A Systems Engineering Management Plan (SEMP) is baselined in Phase A to document how systems engineering requirements and practices will be addressed throughout the program life cycle.

Systems Engineering Management Plan (SEMP)

The SEMP provides the following:

- Specific information on the technical effort and describes what processes will be used
- Shows how the processes will be applied using appropriate activities,
- how the project will be organized to accomplish the activities, information flow within the organization, decision making structure, and the resources required for accomplishing the activities.

The process activities are driven by critical events during any phase of a life cycle (including operations) that set the objectives and work product outputs of the processes, and how the processes are integrated. The SEMP provides the communication bridge between the project management team and the engineering discipline teams. It also facilitates effective communication within the discipline teams. The SEMP provides the framework to realize the appropriate work products that meet the entry and exit criteria of the applicable project life-cycle phases to provide management with necessary information for assessing technical progress

Example: Imaging Spectroradiometer (Concept and Technology Development)

During the *Concept and Technology Development* phase, an imaging spectroradiometer technology will be selected by the project team. Also, working with stakeholders, optimal spacecraft orbits will be determined, launch opportunities will be identified, and the concept of operations will be developed. For example: in support of fire detection, the imaging spectroradiometer data collection approach, the data distribution methods and the operational data usage approach will be determined.

In Phase A, the effort focuses on allocating functions to items of hardware, software, and to humans. System functional and performance requirements, and architectures and designs, become firm. System tradeoffs and subsystem tradeoffs iterate back and forth, collaborating with subject matter experts in the effort to seek out more cost-effective designs. A method of determining life-cycle cost (i.e., system-level cost-effectiveness model) is refined to compare cost impacts for each of the different alternatives. (Trade studies should precede –rather than follow – system design decisions.) Major products to this point include an accepted functional baseline for the system and its major end items. The effort also produces various engineering and management plans to prepare for managing the project's downstream processes such as verification and operations.

System Requirements Review (SRR)

The SRR evaluates the functional and performance requirements defined for the system and the preliminary program or project plan and ensures that the requirements and selected concept will satisfy the project.

System Definition Review (SDR)

The SDR review evaluates whether the proposed architecture is responsive to the functional and performance requirements and that the requirements have been allocated to all functional elements of the system concept.

Student Activity:

Based on the previous student concept of operation, students will conduct the listed activities and produce the listed products for a System Requirements Review (SRR) and System Design Review (SDR):

- Review and update documents baselined in Pre-Phase A if needed
- Develop and baseline top-level requirements and constraints including internal and external interfaces
- Allocate system requirements to functions and to next lower level
- Validate requirements
- Baseline plans
  - Systems Engineering Management Plan
  - Control plans such as the Risk Management Plan and Safety Plan
  - Other cross-cutting and specialty plans deemed necessary, such as quality control plan, parts management plan, and mn1logistics plan
- Develop preliminary Verification and Validation Plan, to include identification of verification and validation tools and techniques
- Identify, analyze, and update risks

3.3 Project Phase B: Preliminary Design and Technology Completion

The purpose of Phase B is for the project team to complete the technology development, engineering prototyping, heritage hardware and software assessments, and other risk-mitigation activities identified in the preliminary design. The project demonstrates that its planning, technical, cost, and schedule baselines are complete and consistent; that the preliminary design complies with its requirements; that the project is sufficiently mature to begin Phase C; and that the cost and schedule are adequate to enable project success with acceptable risk. It is at the conclusion of this phase that the project commits to accomplishing the project's objectives for a given cost and schedule. Systems engineers are involved in this phase to ensure the preliminary designs of the various systems will work together, are compatible, and are likely to meet the customer expectations and applicable requirements.

During Phase B, activities establish an initial project baseline, which includes a formal flow down of the project-level performance requirements to a complete set of system and subsystem design specifications for corresponding preliminary designs. The technical requirements should be sufficiently detailed to establish firm schedule and cost estimates for the project. It also should be noted that Phase B is where the top-level requirements and the requirements flowed down to the next level are finalized and placed under configuration control.

While the requirements should be baselined in Phase A, changes resulting from the trade studies and analyses in late Phase A and early Phase B may result in changes or refinement to system requirements.

Example: Imaging Spectroradiometer (Requirements Flow Down)

During the *Preliminary Design* phase, the project team will develop lower-level requirements. The requirements will define the capabilities of the imaging spectroradiometer or the properties of the spectroradiometer that meets the stakeholder's objectives to detect fires from space. Based on the ConOps, at this phase, the sample flow down requirements are presented in the table below:

Sample Flow Down Requirements	
1.0	The imaging spectroradiometer shall have the ability to detect fires from Space
1.1	The imaging spectroradiometer shall have the ability to detect the thermal signature of fires on the Earth's surface
1.2	The imaging spectroradiometer shall have the ability to detect fires from a low Earth orbit (up to 1,200 miles above the Earth)

It is important in Phase B to validate design decisions against the original goals and objectives and ConOps. All aspects of the life cycle should be considered, including design decisions that affect training, operations resource management, human factors, safety, environment, and maintainability and supportability.

The Phase B baseline consists of a collection of evolving baselines covering technical and business aspects of the project: system (and subsystem) requirements and specifications, designs, verification and operational plans, and so on in the technical portion of the baseline, and schedules, cost projections, and management plans in the business portion. Establishment of baselines imply the implementation of configuration management procedures.

Preliminary Design Review (PDR)

The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. It shows that the correct design options have been selected, interfaces have been identified, and verification methods have been described. The PDR should address and resolve critical, system-wide issues and show that work can begin on detailed design.

Phase B culminates in a series of Preliminary Design Reviews (PDRs), containing the system-level PDR and PDRs for lower-level end items, such as parts and components, as appropriate. The PDRs reflect the successive refinement of requirements into designs. Design issues uncovered in the PDRs should be resolved so that final design can begin with unambiguous design-to specifications. From this point on, almost all changes to the baseline are expected to represent successive refinements, not fundamental changes.

Significant design changes at and beyond Phase B become increasingly expensive.

Example: Imaging Spectroradiometer (Preliminary Design and Technology Completion)

During the *Preliminary Design and Technology Completion* phase, the design of the imaging spectroradiometer will be completed. Any additional design changes beyond this point are expected to be refinements. Additionally, the hardware components will be selected, and software modules understood.

This phase culminates with a preliminary design review allows stakeholders and subject matter experts to review the design and its alignment with the requirements.

Student Activity:

Students will view the design-related video:

https://www.youtube.com/watch?v=aXQ2lO3ieBA

Student Activity:

Based on the previous student concept of operation, students will conduct the listed activities and produce the listed products for a Preliminary Design Review (PDR):

- Review and update documents baselined in previous phases
- Monitor progress against plans
- Develop the preliminary design
    - Identify one or more feasible preliminary designs including internal and external interfaces
    - Perform analyses of candidate designs and report results
    - Conduct engineering development tests as needed and report results
    - Select a preliminary design solution
- Develop operations plans based on matured ConOps
    - Define system operations as well as contingency planning
- Report technology development results
- Update cost range estimate and schedule data
- Identify and update risks
- Develop preliminary plans
    - Decommissioning Plan
    - Disposal Plan

3.4 Project Phase C: Final Design and Fabrication

The purpose of Phase C is to complete and document the detailed design of the system that meets the detailed requirements and to fabricate, code, or otherwise realize the products. During Phase C, activities establish a complete design (product baseline), fabricate, or produce hardware, and code software in preparation for integration. Trade studies continue and results are used to validate the design against project goals, objectives, and ConOps. Engineering test units more closely resembling actual hardware are built and tested to establish confidence that the design will function in the expected environments. representatives of the user population participate in operations evaluations of the design, use, maintenance, training procedures, and interfaces. Engineering specialty and crosscutting analysis results are integrated into the design. The manufacturing process and controls are defined and validated. Systems engineers are involved in this phase to ensure the final detailed designs of the various systems will work together, are compatible, and are likely to meet the customer expectations and applicable requirements. During fabrication, the systems engineer is available to answer questions and work any interfacing issues that might arise.

Example: Imaging Spectroradiometer (Final Design and Fabrication)

During the *Final Design and Fabrication* phase imaging spectroradiometer undergo final design and will be fabricated. This phase will culminate with a baseline hardware build, the completion of the software build and system interfaces to the spacecraft.

All the planning initiated back in Phase A for the testing and operational equipment, processes and analysis, integration of the crosscutting and engineering specialty analysis, and manufacturing processes and controls is implemented. Configuration management continues to track and control design changes as detailed interfaces are defined. At each step in the successive refinement of the final design, corresponding integration and verification activities are planned in greater detail. During this phase, technical parameters, schedules, and budgets are closely tracked to ensure that undesirable trends (such as an unexpected growth in spacecraft mass or increase in its cost) are recognized early enough to take corrective action. These activities focus on preparing for the CDR, Production Readiness Review (PRR) (if required), and the SIR.

Critical Design Review (CDR)

The CDR demonstrates that the maturity of the design is appropriate to support proceeding with full scale fabrication, assembly, integration, and test. CDR determines if the technical effort is on track to complete the system development, meeting mission performance requirements within the identified cost and schedule constraints.

Production Readiness Review (PRR)

A PRR is held for projects developing or acquiring multiple or similar systems greater than three or as determined by the project. The PRR determines the readiness of the system developers to efficiently produce the required number of systems. It ensures that the production plans; fabrication, assembly, and integration-enabling products; and personnel are in place and ready to begin production.

System Integration Review (SIR)

An SIR ensures segments, components, and subsystems are on schedule to be integrated into the system. Integration facilities, support personnel, and integration plans and procedures are on schedule to support integration.

Phase C contains a series of CDRs containing the system-level CDR and CDRs corresponding to the different levels of the system hierarchy. A CDR for each end item should be held prior to the start of fabrication/production for hardware and prior to the start of coding of deliverable software products. Typically, the sequence of CDRs reflects the integration process that will occur in the next phase; that is, from lower level CDRs to the system-level CDR. Projects, however, should tailor the sequencing of the reviews to meet the needs of the project. If there is a production run of products, a PRR will be performed to ensure the production plans, facilities, and personnel are ready to begin production. Phase C culminates with an SIR. Training requirements and preliminary operations procedures are created and baselined. The final product of this phase is a product ready for integration.

Student Activity:

The purpose of the Final Design and Fabrication phase is to complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end-product. Based on a selected concept of operations with an engineered subsystem, students will conduct the listed activities and produce the listed products for a Critical Design Review (CDR):

- Review and update documents baselined in previous phases
- Monitor progress against plans
- Develop and document hardware and software detailed designs
  - Fully mature and define selected preliminary designs
  - Add remaining lower-level design specifications to the system architecture
  - Perform and archive trade studies
  - Perform development testing at the component or subsystem level
  - Fully document final design and develop data package
- Develop/refine and baseline plans
  - Interface definitions
  - Implementation plans
  - Integration plans
  - Verification and validation plans
  - Operations plans
- Develop/refine preliminary plans
  - Decommissioning and disposal plans, including human capital transition
  - Communications (including command and telemetry lists)
- Develop/refine procedures for
  - Manufacturing and assembly
  - Verification and validation
- Fabricate (or code) the product
- Identify and update risks
- Monitor project progress against project plans
- Finalize appropriate level safety data package and updated security plan
- Identify opportunities for preplanned product improvement

3.5 Project Phase D: System Assembly, Integration and Test, Launch

The purpose of Phase D is to assemble, integrate, verify, validate, and launch the system. These activities focus on preparing for the Operational Readiness Review (ORR). Activities include assembly, integration, verification, and validation of the system, including testing the flight system to expected environments within margin. Other activities include updating operational procedures, rehearsals and training of operating personnel and crew members, and implementation of the logistics and spares planning. For flight projects, the focus of activities then shifts to prelaunch integration and launch. System engineering is involved in all aspects of this phase including answering questions, providing advice, resolving issues, assessing results of the verification and validation tests, ensuring that the V&V results meet the customer expectations and applicable requirements, and providing information to decision makers for go/no-go decisions.

Verification and Validation

Product Verification and Product Validation processes may be similar in nature, but the objectives are fundamentally different:

- Verification of a product shows proof of compliance with requirements—that the product can meet each "shall" statement as proven though performance of a test, analysis, inspection, or demonstration (or combination of these).
- Validation of a product shows that the product accomplishes the intended purpose in the intended environment—that it meets the expectations of the customer and other stakeholders as shown through performance of a test, analysis, inspection, or demonstration.

The planning for Phase D activities was initiated in Phase A. The planning for the activities should be performed as early as possible since changes at this point can become costly. Phase D concludes with a system that has been shown to be capable of accomplishing the purpose for which it was created.

Example: Imaging Spectroradiometer (System Assembly, Integration and Test, Launch)

During the *System Assembly, Integration and Test, Launch* phase, the imaging spectroradiometer will be tested (verified) to determine if the device meets the project requirements, based on system analysis, inspection and demonstrated capabilities. Next, the imaging spectroradiometer will be integrated within the spacecraft system. It will then be tested (validated) again, to determine if it meets the intended purpose of the requirements, while operating within the spacecraft. All other elements of the spacecraft will be assembled, then the spacecraft will be launched into space. Once in space, the capabilities of the imaging spectroradiometer will be validated again.

Operational Readiness Review (ORR)

The ORR examines the actual system characteristics and procedures used in the system or end product's operation. It ensures that all system and support (flight and ground) hardware, software, personnel, procedures, and user documentation accurately reflect the deployed state of the system.

Student Activity:

The purpose of the System Assembly, Integration and Test, Launch phase is to assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it will be able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use. Based on a selected concept of operations with an engineered subsystem, students will conduct the listed activities and produce the listed products for an ORR:

- Update documents developed and baselined in previous phases
- Monitor project progress against plans
- Identify and update risks
- Integrate/assemble components
- Perform verification and validation on assemblies according to the V&V Plan and procedures
    - Perform system qualification verifications
- Perform system acceptance verifications and validation(s) (e.g., end-to-end tests encompassing all elements
    - Assess and approve verification and validation results
    - Resolve verification and validation discrepancies
    - Baseline verification and validation report
- Prepare and baseline
    - Operator's manuals
    - Maintenance manuals
    - Operations handbook
- Prepare launch, operations, and ground support sites including training as needed
    - Train on contingency planning
    - Confirm system and support elements are ready for system implementation
    - Perform planned operational verification(s) and validation(s)

3.6 Project Phase E: Operations and Sustainment

The purpose of Phase E is to conduct the prime system design to meet the initially identified need and to maintain support for that need. The products of the phase are the results of the system design and performance of the system. Detailed operational documentation and training material is produced.

Systems engineering personnel continue to play a role during this phase since integration often overlaps with operations for complex systems. Some programs have repeated operations/flights which require configuration changes and new project objectives with each occurrence. And systems with complex sustainment needs or human involvement will likely require evaluation and adjustments that may be beyond the scope of operators to perform. Specialty engineering disciplines, like maintainability and logistics servicing, will be performing tasks during this phase as well. Such tasks may require reiteration and/or recursion of the common systems engineering processes.

Additionally, software development may continue well into Phase E. For example, software for a planetary probe may be developed and uplinked while in-flight. Another example would be new hardware developed for space station increments.

Example: Imaging Spectroradiometer (Operations and Sustainment)

> During the *Operations and Sustainment* phase, the imaging spectroradiometer will collect imaging data, decern which collected information represents fires on the Earth's surface and transmit the fire-related information to the spacecrafts communications system. Additionally, during this time operational changes may be made to the imaging spectroradiometer, based on things such as spacecraft orbital timing, cloud cover of events of interest on the Earth's surface. Furthermore, the imaging spectroradiometer may require maintenance related software updates over the lifetime of its operations.

Student Activity:

> The purpose of the Operations and Sustainment phase is to conduct the system design and meet the initially identified need and maintain support for that need. Implement the system design operations plan.

- Conduct the intended prime system design
- Provide sustaining support as planned
  - Collect engineering and science data
  - Maintain and approve operations and maintenance logs
  - Maintain and upgrade the system
  - Identify and update risks
  - Address problem/failure reports
  - Process and analyze system design data
- Prepare for deactivation, disassembly, decommissioning as planned
- Capture lessons learned
- Complete post-operational evaluation reports
- Develop final system design report

3.7 Project Phase F: Closeout

The purpose of Phase F is to implement the systems decommissioning and disposal planning and analyze any returned data and samples. The products of the phase are the results of the system design. The system engineer is involved in this phase to ensure all technical information is properly identified and archived, to answer questions, and to resolve issues as they arise.

Phase F deals with the final closeout of the system when it has completed its project intent; the time at which this occurs depends on many factors. For a flight system that returns to Earth after a short duration, closeout may require little more than de-integrating the hardware and returning it to its owner. On flight projects of long duration, closeout may proceed according to established plans or may begin as a result of unplanned events, such as failures. Alternatively, technological advances may make it uneconomical to continue operating the system either in its current configuration or an improved one.

Example: Imaging Spectroradiometer (Closeout)

During the *Closeout* phase, systems decommissioning, and disposal are completed. Additionally, data from the imaging spectroradiometer should be analyzed. The imaging spectroradiometer will be mounted on a spacecraft in low earth orbit. When the spacecraft reaches the end-of-life, the orbit will be deorbited. This is accomplished by allowing the orbit to slowly decay until the satellite eventually burns up in the Earth's atmosphere.

Student Activity:

The purpose of the Operations and Sustainment phase is to conduct the system design and meet the initially identified need and maintain support for that need. Implement the system design operations plan.

- Dispose of the system and supporting processes
- Document lessons learned
- Baseline project final report

4.0 Various Lifecycle Models

Though this curriculum is based primarily on the waterfall lifecycle method of Systems Engineering, there are other lifecycle process models. According to the INCOSE Systems Engineering Handbook v3.2.2, a few of them include the Agile, Vee, and spiral models [3]:

> The Agile development model may offer more flexibility by providing a tailoring framework, based on opportunity to simplify control methods and to assess the risks in so doing. The Agile development model provides integration and verification as part of the build cycle and validation continuously throughout the process via direct customer/user involvement. This differs mainly from the waterfall model by reducing the requirement of a hierarchical approach.
>
> Another method is the Vee model. This approach is used to visualize the system engineering focus, particularly during the Concept and Development Stages. The Vee highlights the need to define verification plans during requirements development, the need for continuous validation with the stakeholders, and the importance of continuous risk and opportunity assessment.
>
> The spiral method combines the iterative, or agile, development process model with elements of the Waterfall model, where requirements are defined in as much detail as possible and successive iterations fill in more detail. The Spiral method provides non-sequential models when practical considerations require a non-linear execution of life cycle stages.

While there are multiple systems engineering lifecycle models, it is crucial to work all the details completely and consistently and ensure that the designs and technical activities of all the stakeholders and organizations remain coordinated.

Reference

[1] NASA Systems Engineering Handbook Rev 2

[2] The Art and Science of Systems Engineering
https://www.nasa.gov/pdf/311199main_Art_and_Sci_of_SE_SHORT_1_20_09.pdf

[3] INCOSE Systems Engineering Handbook v3.2.2