SAND2016-3620R

SANDIA REPORT
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April 2016

Systems Engineering Applied: A Case Study in the Implementation of Successful Systems

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Abstract

The application of Systems Engineering (SE) principles has emerged to manage complex systems from a concept to the successful realization and implementation of the system. Multiple Research and Development (R&D) programs at Sandia National Laboratories (SNL) have implemented these principles and have maximized their efforts in the realization of successful systems. The Primary Standards Laboratory (PSL) at SNL has avoided the full implementation of such principles which has stalled the development of new and efficient calibration systems. The objective of this project is to introduce SE to the PSL and develop a framework of best practices that can be utilized to expedite the development and deployment of accurate and efficient testing systems throughout the PSL. A Case Study will be presented for the principles of the SE development lifecycle in a R&D environment to maximize the PSL's efforts in a requirements-driven environment.

ACKNOWLEDGMENTS

My completion of this project could not have been accomplished without the support from the Primary Standard Labs staff and High Confidence System Environments staff. To Steven Aragon, Ricky Sandoval, and Anthony Matta – thank you for allowing me time from you to research and write.

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1. EXECUTIVE SUMMARY

The application of Systems Engineering (SE) principles has emerged to manage complex systems from a concept to the successful realization and implementation of the system. Multiple Research and Development (R&D) programs at Sandia National Laboratories (SNL) have implemented these principles and have maximized their efforts in the realization of successful systems. The Primary Standards Laboratory (PSL) at SNL has avoided the full implementation of such principles due to the lack of knowledge and a perception that such principles inhibit the development of new calibration technologies. That perception has stalled the development of new and efficient methods of supporting SNL with calibration systems to support equipment used in multiple R&D projects. These perceptions will be addressed with the application of SE as an integrated approach to a case study in the development of an RF calibration system.

According to the International Council on Systems Engineering (INCOSE), the term SE dates back to Bell Laboratories in the early 1900s with major application of SE during World War II. INCOSE continues to explain that the first attempt to teach SE as we know it today came in 1950 at MIT by Mr. Gilman, Director of SE at Bell. The objective of SE is the development and deployment of systems that meet the customer’s needs. As systems become more complex, SE has emerged as a systematic approach to the development of successful systems. Its principles have been used to address potential critical issues in the research, design, and development of systems in multiple R&D projects at SNL. This project will apply SE systematic approach to the development of an RF calibration system that will serve as a guide and an educational resource for the benefit of the PSL.

The objective of this project is to introduce SE to the PSL and develop a framework of best practices that can be utilized to expedite the development and deployment of accurate and efficient testing systems throughout the PSL. A Case Study will be presented for the principles of the SE development lifecycle in a R&D environment to maximize the PSL’s efforts in a requirements-driven environment. The approach for this project will consist of model based methods to systems engineering for the rapid development and deployment of systems that meet the PSL’s needs. Various models will be presented with the intention of extracting their strong points and combining them for a new model that streamlines the development and deployment of successful systems. The new model will be supported with a trade study analysis and reinforced

with SE concepts such as systems thinking and systems architecture and design. The new model will be applied in a case study of the development of a power sensor calibration system.

2. INTRODUCTION

This project provides an overview of SE and lays out a framework of SE principles application with a case study in the development of an RF power sensor calibration station that could be applied at the PSL. The project's purpose is to educate readers with the SE process and provide a framework of best practices that can be applied to the development of new systems. The framework is presented in the form of a case study applied to a real world problem to fulfill a need. The case study will put SE in practice by performing a trade study to identify potential solutions and ultimately select and implement the system that meets the stakeholders' needs. The systems validation is future work for the PSL and will be performed through rigorous testing with statistical analysis of results and presented for formal review and acceptance before use.

SE is a term that dates back to the 1900s with major applications during World War II. WWII military projects were more complex increasing interactions of subject matter experts and systems with sub-systems. The need for a structured approach to complex systems in the 1900s laid the foundation of SE as it is known today. The effectiveness of the SE approach continues to be driven by tight schedules that require the development and design of complex systems, subsystems, testing, and training. SE efficiency is achieved through highly developed management tools and principles that ensure the development and deployment of successful systems.

This project is arranged in **Error! Reference source not found.** sections. Section **Error! Reference source not found.** is the Executive Summary that provides a synopsis of the need for SE principles applied to the PSL. Section **Error! Reference source not found.** is the introduction to the project's organization layout. Section **Error! Reference source not found.** is background information related to the primary standards labs responsibilities at Sandia National Labs. This section outlines the problem which gives insight to the overall need for systems engineering application for successful systems. Section **Error! Reference source not found.** is the technical approach to the foundation framework applied in the development and realization of successful systems. It is a roadmap that offers options to practitioners in developing such systems that can be customized to meet stakeholder's needs. It is also a systems engineering primer for the reader to understand the process and its importance in developing systems. It is a brief overview and is intended to give the reader a starting point that can be expanded upon with more research on the topic of interest. The recommendation and justification for Model Based

Systems Engineering (MBSE) will be explored with the intention of extracting its strongest points for a streamlined rapid development and deployment model that meets the PSL's needs. Section **Error! Reference source not found.** is the implementation of MBSE and future work required prior to releasing the selected power sensor system for calibrations. Section **Error! Reference source not found.** is the conclusion for SE using the model based approach to successful system development. This section also summarizes the SE approach and recommends alternative methods of applying SE to developing systems for the PSL.

Section	Purpose
1	Synopsis of the project and application of SE to the PSL.
2	Organization layout of the project.
3	PSL's role at Sandia National Labs.
4	Technical Approach of systems engineering applied to system development. This section recommends MBSE and applies concepts mentioned in this project to a real world problem.
5	Implementation of MBSE and future work.
6	Conclusion and alternative recommendation for MBSE for successful system development.

Table 1 Project layout

3. BACKGROUND

The PSL at SNL oversees and provides technical oversight, guidance, and measurement assurance for the standards and calibration program for the Department of Energy (DOE) and National Nuclear Security Administration (NNSA). PSL members develop and maintain primary standards traceable to the National Institute of Standards Technology (NIST) and are authorized to calibrate and certify customers reference standards. Additionally, the PSL serves as the Contractor Standards Laboratory for SNL which includes performing calibrations for Measurement & Test Equipment (M&TE) for all SNL organizations. It is the PSL's mission to assure the integrity of measurements for NNSA and DOE by certifying standards and measurement equipment and advancing the science of metrology by educating stakeholders. High operating expectations are set to meet the requirements of the International Standard for General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2005(E), and is accredited by NIST.

For the past 30 years the PSL had a limited amount of customers that worked on R&D projects which used equipment requiring calibration. The limited amount of projects gave the PSL the ability to manually calibrate, certify hardware, and meet customer demands. The advancement of scientific and nuclear technologies has led to multiple research and development groups requiring advanced calibrated equipment traceable to NIST. The higher level of calibration detail requirements for electronic components and quantity of items has changed the manual calibration dynamics exposing needs in new calibration methods and systems. This exposure has stressed PSL calibration procedures and the ability to keep up with new calibration methods to calibrate and certify the latest hardware used in multiple research and development projects.

It is Sandia's policy that all M&TE that can affect the quality of a product or service delivered by SNL be sent to the PSL for calibration. There is not an exception for R&D activities because R&D activities eventually lead to products or services. The lack of calibration station development for newer technological equipment has forced the PSL to send hardware to external calibration sites for calibration and certification. For example, there are a total of 132 RF Power Sensors that require periodic calibration according to the manufacturer's recommendation (usually every 12 months). Based on the variability, there is always at least two items sent out for calibration every week. The current process is as follows (Figure 1): A customer sends a power sensor to the PSL. Since the PSL does not have the capability to calibrate the item, they start the paperwork to send the item to the external calibration site. The item is shipped to the external site. The external site performs the calibration and then ships the item back to the PSL. The PSL performs a required post analysis of the work performed by the external site and then closes out the paperwork. The item is finally returned to the customer.

Figure 1 Current Process

The average turnaround time from the external calibration lab is 8 days with the additional 5 days it takes the PSL to complete required post analysis and paper work. The cost of calibration for each item including shipping is $500. This process is expensive for the PSL customers and time consuming with an average turnaround time of 13 days (including 5 extra days from the PSL) which has created an opportunity to apply SE principles to find solutions to meet challenges without outsourcing equipment for calibration and improve customer satisfaction.

The PSL is in need of a structure/framework for rapid development and deployment of successful calibration systems to provide quality assurance and credibility to stakeholders. At the request of the PSL, this project will focus on applying SE to the development and deployment of an RF Power Sensor calibration system. The case study presented in section 4 will focus on the SE application to the development of a power sensor calibration system that will calibrate RF power sensors with frequencies from 9 kHz to 50 GHz and power levels from -70 dBm to 44 dBm.

3.1 The Importance of Calibrated Power Measurements

The need for power measurements was first required with the introduction of RF and microwave systems. In the early stages of this new technology, measurements of high power system signals were attained by having an artifact absorb a large portion of system power and measuring the heat buildup versus time. Power measurement continued to advance with the introduction of detection crystal technology which was better matched to perform at higher RF and microwave frequencies. During the 1950s and 1960s coaxial and waveguide thermistors facilitated power measurements and during the 1970s thermocouple sensor technology was developed along with digital instrumentation.

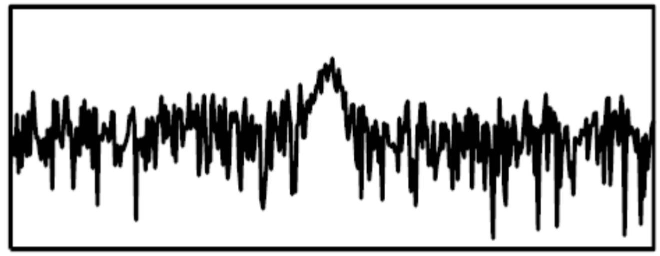

Figure 2 Lower power results in higher noise levels (Agilent Technologies, 2005)

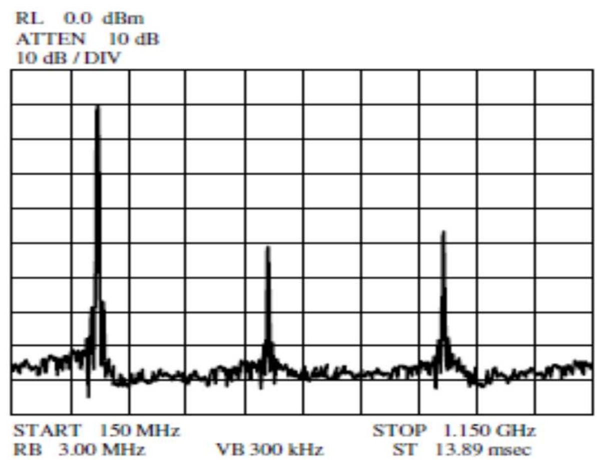

Figure 3 Higher power results in higher distortion levels (Agilent Technologies, 2005)

Power in electrical terms is the amount of energy that flows per time. Power is measured in Watts which is the equivalent of one joule per second. RF power sensors are used to measure RF power, which is generally in the 3 kHz to 300 GHz range. RF power is measured in dBm, which is the power ratio in decibels referenced to 1 mW. Therefore, an RF signal with a power level of 0 dBm is the same as 1 mW. Low power levels result in higher noise levels (**Error! Reference source not found.**) while higher power levels result in distortion (**Error! Reference source not found.**). It is critical for system performance to have proper linear power at every frequency level for each component.

Calibrations provide quality assurance for R&D projects by ensuring power sensors are operating within manufacturer's specifications. Calibration is performed according to a documented procedure and compares the power sensors performance against a standard of known accuracy. The power sensor is adjusted if the tolerance is above or below manufacturers suggested limits. The power sensor is returned to the customer with a test report which documents the procedure performed, results, standards used, and calibration technician.

Quality assurance provides stakeholders traceability, accuracy, reliability, precision, and validity of data for research management to drive decisions for product development. The quality assurance behind the calibration gives Sandia National Laboratories confidence to deliver working product to customers within the National Security Enterprise.

The importance of SE for this project is to provide a framework of best practices suited for the problem at hand. The SE concepts applied to the framework for this project are Systems Thinking, Trade study analysis, and System Architecture and Design applied using MBSE methods to effectively communicate requirements and system design for development and implementation that meets the stakeholder's needs.

The Systems Thinking process will be used to understand the interactions between system components and the resulting behavior of unintended consequences that may result from such interactions. It will provide a methodical approach to understanding system behaviors and problem situations to identify solutions to these problems.

System architecture and design process is where system architecture is refined through alternative architectures "through several views and models, to assess the properties of these alternatives, and to select appropriate technological or technical system elements that compose the system." (Long & Zane, 2011). It is where the system is ultimately defined through iterations of the system design process and supported by the subject matter experts for a system that meets the stakeholder's needs.

Trade study analysis assists with supporting the decisions needs of the system engineering process by defining requirements, refining the system concept, evaluating alternative systems and determining the need of additional analysis for the best possible solution that meets stakeholders needs.

3.2 Stakeholders

The primary stakeholder as a whole for this project is the PSL. The PSL however is composed of multiple calibration labs such as Alternating Current, Direct Current, Electrical, Mechanical and Microwave labs. Each lab is staffed with engineers, team leads, and calibration technicians reporting to management that oversees daily operations. The power sensor system is for the Microwave lab and, for this project the PSL is referred to as the calibration subject matter expert for the nuclear weapons enterprise and active stakeholders are refined to the labs within the PSL.

The expectation is to learn SE principles and develop a SE framework for development and deployment of successful calibration systems that will allow them to keep up with rapid equipment technological calibration requirement changes. Among other important stakeholders for successful implementation of the system are: Sandia National Labs, the National Nuclear Safety Administration (NNSA), and the National Security Enterprise.

Active Stakeholder	Passive Stakeholders
PSL Microwave Team Lead	Sandia National Laboratories
PSL Microwave Engineering Staff	National Nuclear Safety Administration
PSL Microwave Calibration Technicians	PSL Customers
PSL Management	National Security Enterprise

Table 2 Stakeholders

Even though the PSL is the active stakeholder and the subject matter expert in calibrations, it is important to recognize the sphere of influence and decisions that can be imposed on the system. An interest map of stakeholders (Table 3) was used to further understand the hierarchy and value of the system to stakeholders.

Stakeholder	Influence	Interests	Concerns
PSL Management	Ensures system performance meets customer, corporate, and NNSA requirements.	Accuracy of data, flexibility, and efficiency.	Safety and budget allocation.
PSL Microwave Engineering Staff	Subject matter expert for power sensor calibrations. Able to determine if a given system is sufficient to perform calibrations.	Cease outsourcing of calibration work than can be performed in house. Decreased turnaround time for calibrations.	Unable to put an "out of the box" or "turnkey" system into use without a thorough review and testing. May need access to source code to validate settings, and algorithms. May need access to raw data to validate mathematical computations.
Sandia National Labs	Ensure System conforms to corporate	Ability of system to meet customer's	Safety; Legal/ethical corporate procedures

	requirements.	requirements. Ensures the PSL has the resources to support customer calibrations.	to guide the bidding process; Ensure fair business practices.
National Nuclear Safety Administration	Ensures system performance meets measuring and test equipment requirements.	Bringing all calibrations internal to the corporation to ensure validity of data.	System Accuracy
National Security Enterprise	Ensure system will validate that the power sensors are working as expected.	System provides accurate data potential to get primary standards calibrated by the system.	Ability to meet customer's needs.
Department of Energy	Ensure system will validate that the power sensors are working as expected.	System provides accurate data.	Safety
Customers (PSL Microwave Customers)	The sensors they own and the accuracies/uncertainties they require drive the requirements for the system.	Able to obtain traceable calibrations to required accuracies/uncertainties.	Cost, turnaround time.

Table 3 Stakeholder interest map

3.3 Stakeholders Expectations

Stakeholder's expectations were expressed through several meetings, interviews and simulations of the current need. The results are charted below with the stakeholder's capability and characteristic requirements for a successful system implementation. Key expectations are marked with an asterisk and are absolutely required and are non-negotiable for any substitution that comprises the system's ability to meet the need. Assumptions for the system are identified as qualified calibration technicians, the proper handling of data (which may or may not be classified), accurate data availability for stakeholder's projects, NIST traceability and the PSL maintaining ISO17025 certification.

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Stakeholders Expectations			
	Capabilities	**Characteristics**	**Stakeholder Ownership**
***Expectation 1**	Calibrate power sensors to manufacturers specifications	Minimal turnaround time to less than 2 weeks.	Calibration Technicians
***Expectation 2**	System Reliability	SME support and minimum downtime.	Engineering Staff
***Expectation 3**	Raw data analysis	Perform tolerance analysis to verify system performance and accuracy.	Engineering Staff/Team Lead
***Expectation 4**	System flexibility	Ability to calibrate various power sensor models and brands. Ability to select compatible standards.	Team Lead
***Expectation 5**	System efficiency	Short duration calibration process.	Team Lead
Expectation 6	Maintainability	Accessibility to hardware components for replacement. Accessibility to software code for calibration optimization.	Calibration Technicians
Expectation 7	Vendor Support	Onsite training.	PSL Management
Expectation 8	Easy to use	Power sensor system user friendly interfaces.	Calibration Technicians
Expectation 9	Affordability	Power sensor system cost meets PSL's budget constraints.	PSL Management

Table 4 Stakeholder expectations. * indicates stakeholder key requirements

3.4 Calibration System concept of Operations

A concept of operations (CONOPS) is a description of the proposed systems daily operations from the user’s perspective. It "describes the proposed system in terms of the user needs it will fulfill, its relationship to existing systems or procedures, and the ways it will be used. Additionally, a CONOPS may focus on communicating the user's needs to the developer or the developer's ideas to the user and other interested parties." (MITRE Corp., 2016)

The following CONOPS communicates the proposed system from the primary stakeholder’s perspective.

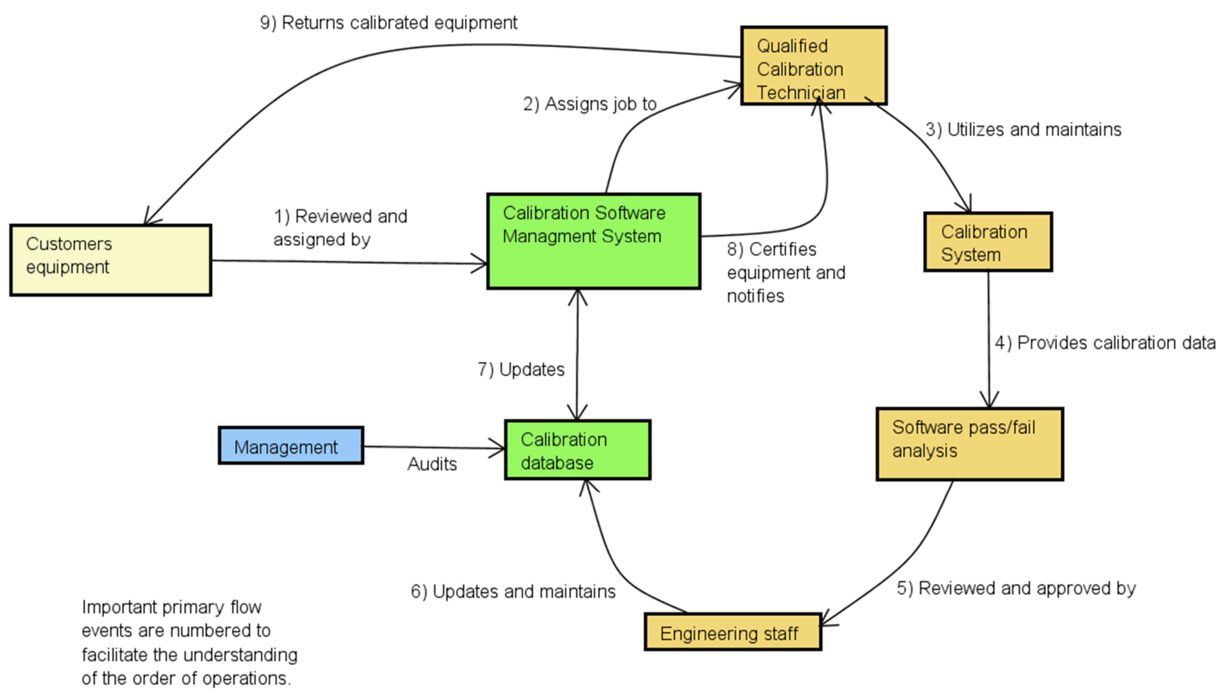

Figure 4 Concept of Operations

The idea behind the new system is to localize the calibration process of power sensors. The system must have stakeholder key requirements for development considerations. The PSL will provide an experienced and certified calibration technician. He or she will have the ability to log into the system which will verify qualifications and certifications associated with the task at hand. The calibration technician will verify all standards for the system are calibrated. He or she will select the proper calibration procedure for the asset to be calibrated, perform calibration, verify data results and store the data to the systems database. Data can be accessed as needed by stakeholders as they work on their projects. The system architecture in Figure 5 reflects functions, operations and components of the calibration system and a trace of high level calibration process.

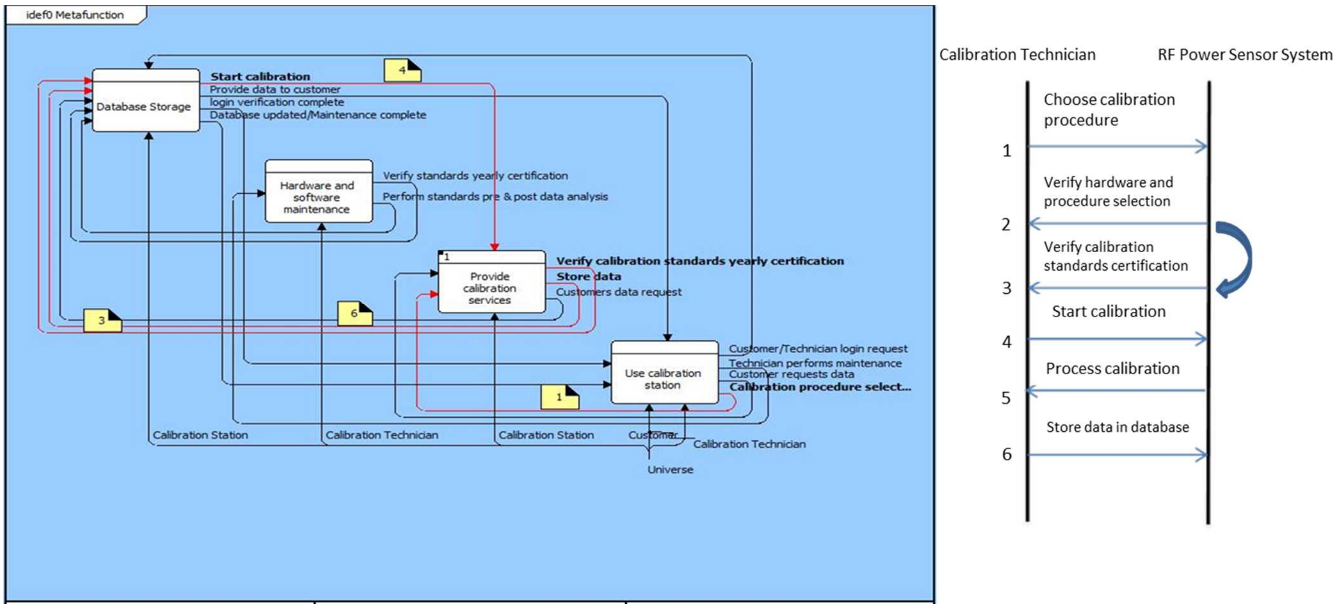

Figure 5 System architecture and high level trace of the calibration process

4. TECHNICAL APPROACH

4.1 Systems Engineering Process Overview

The SE process for this project is twofold; introduce the PSL to SE and rapid development and deployment of successful calibration systems that meet the needs of the PSL. Concepts supporting the SE process for this project are Systems Thinking, trade study analysis process, and System Architecture and Design using the MBSE approach. The previously mentioned concepts are areas of interest to PSL subject matter experts (SME's) as an introduction to SE and its application to the development of successful systems. Table 5 has the recommended SE concept goals and supporting objectives to facilitate the visualization of the systems goal.

SE Concept	Supporting Objective
MBSE	• Facilitate SE education. • Increase communication effectiveness between stakeholders.
Systems Thinking	• Facilitate the understanding of the systems interactions with subsystems.
Trade Study Analysis	• Understand stakeholder requirements. • Support decisions of the SE process. • Evaluate alternative systems. • Develop system concept.
System Architecture and Design	• Define functional view. • Define physical view. • Develop system architecture.

Table 5 SE Concepts and Objectives

As mentioned before, the PSL requested the project application to the development of a power sensor system. To facilitate the understanding of SE application to system development, it was decided to explain the SE concept followed by the application to the power sensor system (as applicable). The model in Figure 6 below was developed based on the PSL's need and is best suited for rapid development and deployment of successful systems while introducing the PSL to the SE process. The model includes system selection and design activities for a balanced solution that meets stakeholder's needs. The purposes of the activities are to:

- Gather stakeholder's needs to analyze and understand the problem to be solved.

- Develop a Concept of Operations based on the stakeholders needs to accurately specify the required system functionality, interfaces, physical characteristics that support the desired system outcome.
- Explore alternative system solutions through the development of various system architecture solutions.
- Perform Trade Study analysis to evaluate and analyze system selection to ensure the best possible solution
- Provide traceability from stakeholder's requirements to system integration.

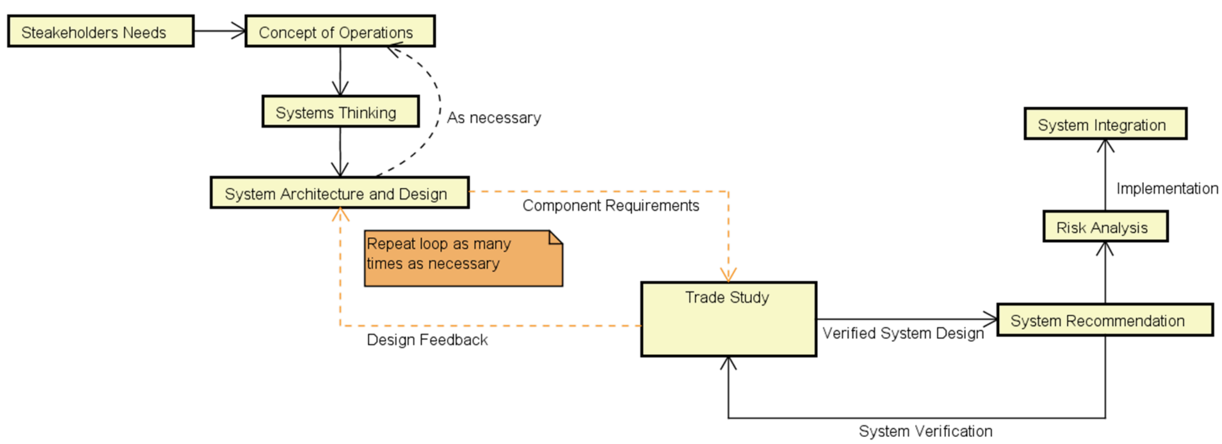

Figure 6 SE Development Model

It is important to understand that the development model can be modified as needed with as many iterations of the model as necessary. Iterations can be taken at each step, loop, or model as a whole to refine the system. The development model addresses SE concepts suitable for the rapid development of successful systems that meets the PSL's needs. It is designed to capture, analyze and manage information associated with the development of calibration systems. The following sections are an introduction to SE and its application to the development of a power sensor calibration system.

4.2 What is Systems Engineering

To understand the definition of systems engineering it is important to define a system. NASA defines a system as "the combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose" (Stevens Institute of Technology, 2012). A system is a set of components functioning together to achieve a greater goal that the component cannot achieve on its own. Since systems are components functioning together for a greater goal, then systems engineering is the development and realization of those successful systems. It is the process involved in developing and realizing a holistic system that meets the stakeholder's needs. The IEEE 1220 standard defines it as "an interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle-balanced system solution that satisfies customer expectations and meets public acceptability."

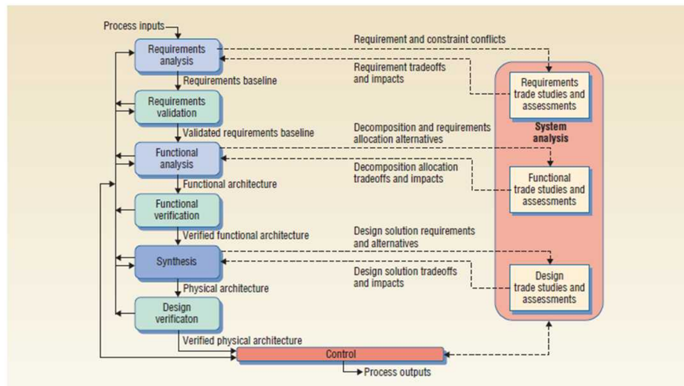

Figure 7 IEEE 1220 Systems engineering Process

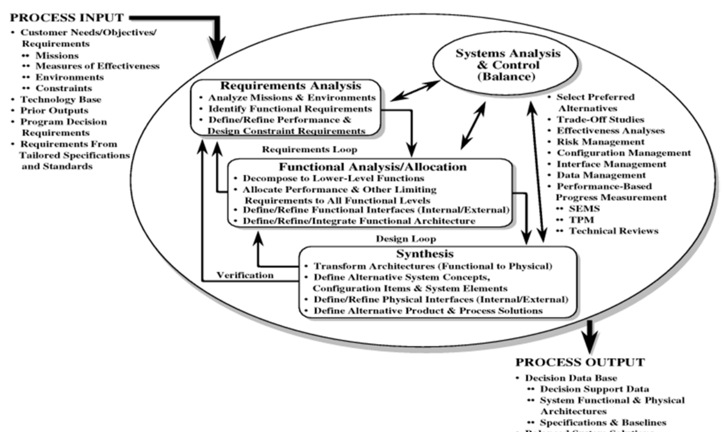

Figure 8 Mil-Std-499B Process Model

A SE process is a process model that defines the primary activities ("WHAT") that must be performed to implement SE (Estefan, 2007). The process is usually implemented at the early stages of a system lifecycle to ensure that the customer and stakeholders needs are met. SE is an iterative problem solving process that can be applied to any system development by transforming stakeholder's needs and requirements to a process description and system product. The iterative approach generates information providing input for the next process requirement. The process is usually applied in sequential order, one level at a time as shown in Figure 7 and Figure 8.

4.3 Recommendation and Justification

The simplicity of IEEE 1220 and MIL-499B models facilitates the understanding and is a good starting point for learning the essential elements of the SE process. However in a document-based SE approach, there are large amounts of information generated about the system that is difficult to accurately maintain. Figure 7 and Figure 8 illustrate the document-based SE process of gathering stakeholder's needs which are processed into system definitions followed by system functions identification. Functions are allocated to system components for a system architecture design that meets the needs of the stakeholder. It is an iterative approach that generates large amount of information for complex projects causing breakdown in communication and efficiency between system engineers and stakeholders. However as systems evolve in complexity, SE has also evolved to address the evolution and gaps in the integration of systems and subsystems. MBSE is the evolved and recommended approach used in this project to facilitate the understanding of SE concepts and for the framework development of successful systems as applied to the development of a power sensor calibration system. In an MBSE approach, information is captured in a system model. The system model is the primary documentation resource and is constantly updated throughout the SE process. The use of an MBSE tool as a central repository is the main distinguishing quality between MBSE and a document-based SE approach.

MBSE	Document-Based SE
Information stored in a central repository.	Difficulty maintaining large amounts of information created by SE's.
Improved communication through the use of models.	Communication breakdown.
Increased productivity.	Decreased productivity.
Rigorous requirements traceability.	Difficulty verifying requirements traceability.

Table 6 Contrast between MBSE and Document-Based SE

The justification for this recommendation is that MBSE is an approach to systems engineering that is flexible and adaptable to unforeseen circumstances throughout the systems lifecycle development. It is an iterative "process of analyzing and solving systems design problems" (Long & Zane, 2011)

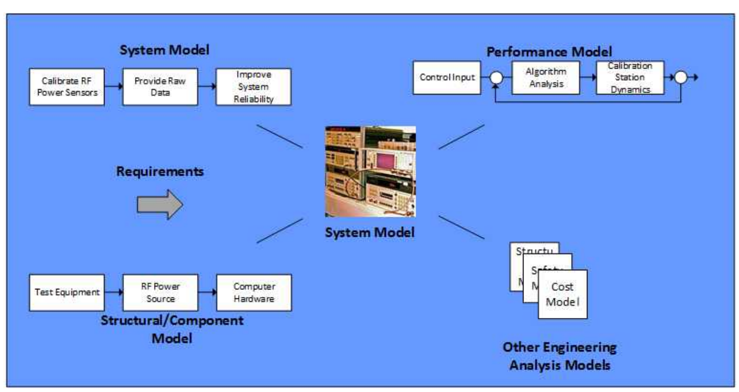

Figure 9 MBSE models

and moves away from the document centric systems engineering paradigm. MBSE facilitates system architecture diagrams and exposes any discrepancies that can be corrected at the early stages of system development. It is “A specified and understood MBSE approach *[that]* will enable the organization to be deliberate and systematic when implementing MBSE.” (Sumner, 2015). MBSE also improves the documentation and communication between stakeholders by implementing models to communicate system boundaries, requirements implementation, process flows, and integration with subsystems. It is an approach that meets the needs of the PSL enabling a framework for the development and deployment of successful systems.

4.4 MBSE Process

MBSE uses diagrams and databases to manage information such as requirements, functional behaviors, architecture, and validation and verification rather than the large document-centric approach. The MBSE process starts with the problem statement which is analyzed and converted into functional behaviors as required by stakeholders for successful system implementation. It helps "separate means from fundamental objectives. This is a critical step, because here we indicate those objectives that are important because they help achieve other objectives and those that are important simply because they reflect what we really want to accomplish." (Clemen & Reily, 2004).

4.4.1 Functional Behaviors

The objective of functional behavior is to create an architecture that serves as the foundation for defining the system. "It is the systematic process of identifying, describing, and relating the functions a system must perform to fulfill its goals and objectives." (National Aeronautics and Space Administration, 2007). In other words it describes what the system must do, but not how it will do it. Functional behaviors must be understandable, unambiguous, comprehensive, complete, and concise with clear definition of what needs to be done to accomplish the objectives. Functional behavior provides information that help understand what the system has to do within its available resources and in what ways it can do it, providing information essential to optimizing physical solutions. They are organized into hierarchies where higher levels in the hierarchy represent general objectives "and the lower levels explain or describe important elements of the more general levels." (Clemen & Reily, 2004).

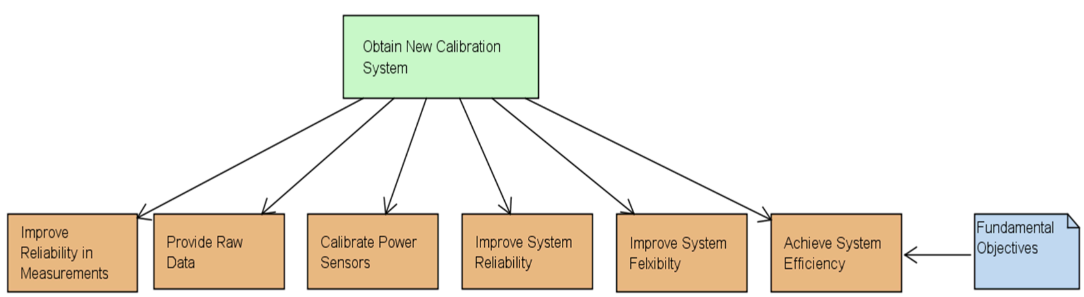

Figure 10 Power Sensor System Functional Behaviors

4.4.2 Means Objective Network

Means objective networks are objectives that help achieve other objectives that support functional behavior objectives. They are organized into networks and can be connected to several objectives. The objective of a means objective network is to extract the importance of objectives and tie them back to the functional behaviors as shown in Figure 11.

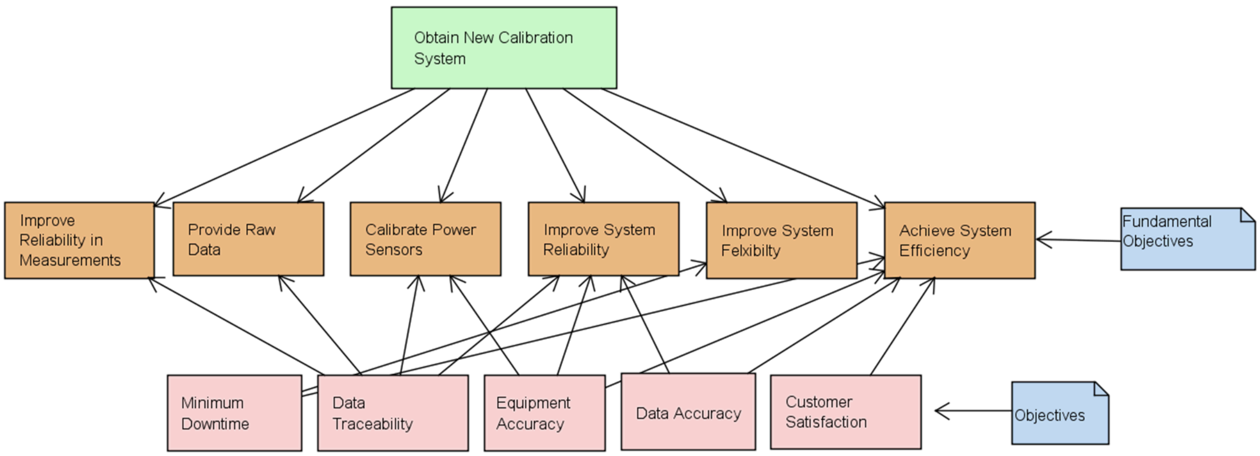

Figure 11 Power Sensor System Means Objective Network

4.4.3 SysML

MBSE addresses Engineering problems through the development and use of System Modeling Language (SysML) for accurately designed solutions. "SysML is a domain-specific modeling language for systems engineering used to specify, analyze, design, optimize, and verify systems." (University of Michigan; SRI International). It is a visual modeling language used to improve the precision of communication between system engineers and stakeholders. A few reasons to use SysML are:

- Compare and contrast "As Is" and "To Be" solutions
- Provide scalable structure for problem solving
- Explore multiple solutions or ideas concurrently with minimal risk
- Detect errors and omissions early in System Development Life Cycle (PivotPoint Technology Corporation, 2003-2015)

Figure 12 is a scenario of PSL's interaction with the system. Engineer staff would have access to raw data to perform tolerance analysis, statistical process control to verify system accuracy, and data analysis of the equipment under test to verify it is within the limitations of manufacturer's specifications. They would also have the ability to provide system support if needed. The calibration technician would calibrate power sensors and perform preventative maintenance according to a recommended schedule. Representative support is optional but highly recommended for the PSL. They provide system support such as training, higher level troubleshooting and preventative maintenance recommendations.

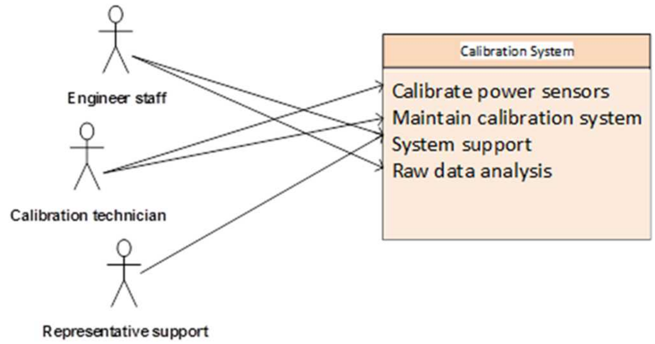

Figure 12 SysML model

4.5 Systems Thinking

Rapid technology advancement and system complexities have created new challenges such as the understanding of system behavior to the component level. System thinking has emerged to provide tools for solutions in understanding complex systems. "System thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static 'snapshots'." (Senge, 1990). It is a simple way at looking at problems and an approach to solutions. System's thinking does not jump into tearing apart the system to understand how it works but "acknowledges the strong interactions between the system components, and the emergent behaviors and unintended consequences that may result from these interactions." (Edson, 2008). It is important to understand the contextual view of the problem and the systems approach to solutions to fully understand the interactions between system components by applying the following Systems Thinking principles:

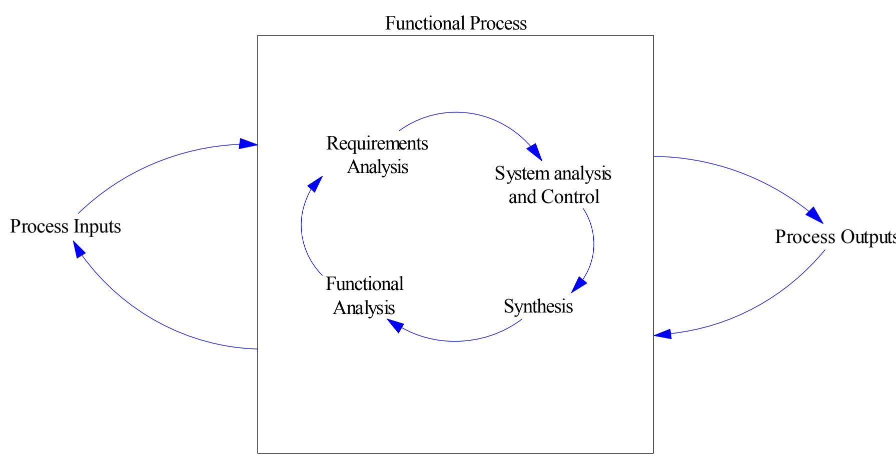

Figure 13 Understanding interactions between process model system components

- A feedback loop is a system structure that causes output from one node to eventually influence input to that same node.
- A feedback loop is either reinforcing or balancing.
- The behavior of all dynamics systems is generated by its feedback loops. Therefore:
    - The important behavior of a system emerges from its key feedback loops.
    - The behavior of a large complex system is generally so counterintuitive that it cannot be correctly understood without modeling the system's key feedback loops. (Harich, 2014)

4.2 System Architecture and Design

IEEE defines architecture as "The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution." System architecture design in SE is where operational need/requirements, concepts, and system requirements are developed into architecture as a foundation to design and develop the system. This is where the framework creation of the stakeholders system view is modeled to reassure system requirements are accurately captured, consolidated and rationalized for the system engineer to develop content structure that satisfies the collective need.

System architecture is composed of a functional view and physical view (

). Functional view develops a functional diagram, identifies internal interfaces, and defines system functions and subsystems as needed. Physical view develops a physical block diagram, identifies physical interfaces, and selects technologies and subsystems.

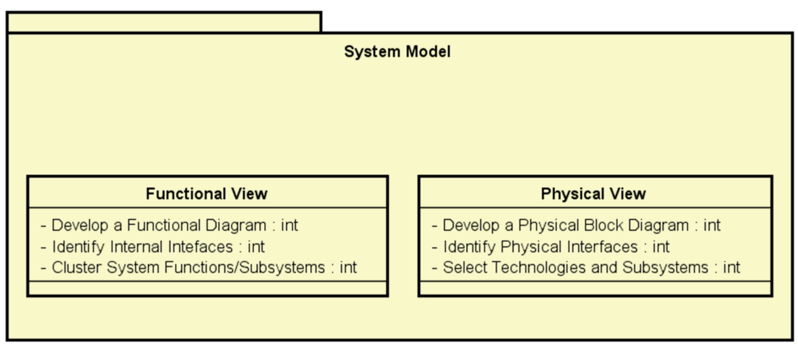

Figure 14 Functional and Physical view of a model

Figure 15 below is the physical block diagram for the power sensor calibration system with the identified physical interfaces.

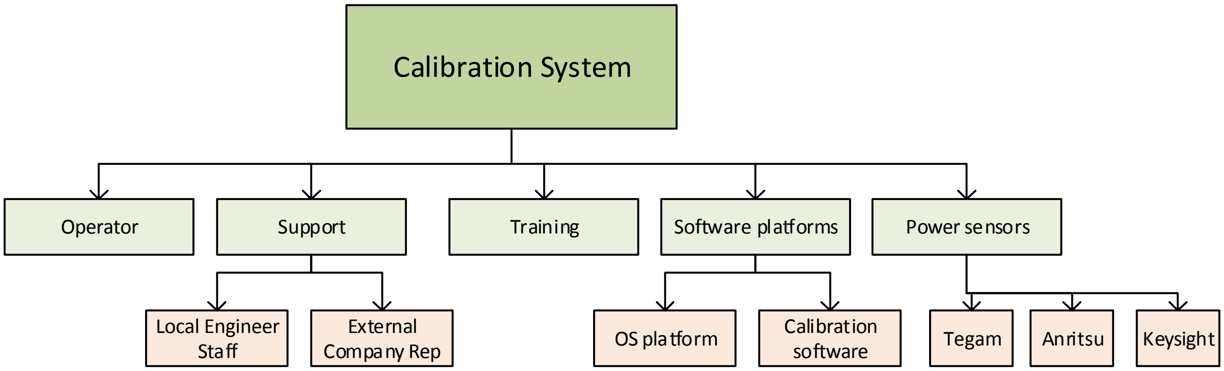

Figure 15 Physical Block Diagram

Figure 16 is the functional block diagram of the power sensor systems components required for successful calibrations.

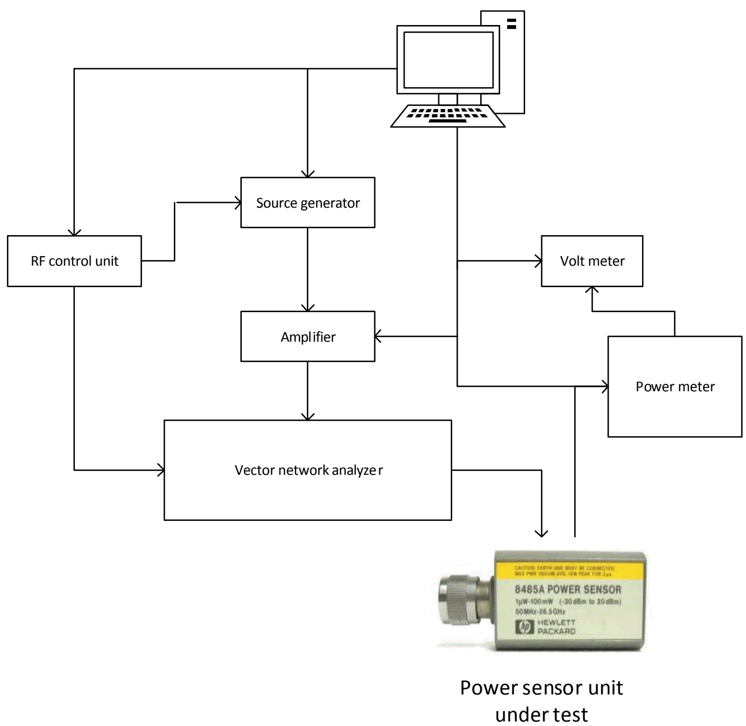

Figure 16 Functional Block Diagram of power sensor system components

4.7 Trade Study

The purpose of a trade study is to support the needs of the SE process. It mitigates cognitive biases when evaluating alternative systems by integrating all considerations needs for stakeholders providing confidence in decisions made. Trade studies refine and develop a system concept further to determine if additional analysis is required giving confidence that all available information has been accounted for a final decision. Trade study analysis for this project is composed of a pair-wise comparison between key stakeholder criteria, utility curves which further define the system, and alternative system evaluations.

4.7.1 Pair-Wise Comparison

A pair-wise comparison is a comparison between stakeholder's criteria to determine requirement priority or preference and helps make decisions for complex problems that best meet stakeholder's needs. The score for this project is based on a 1-5 scale as shown in Table 7. The stakeholder was asked to compare the requirements and based on the scoring scale assign a value that best represents the importance of the requirement on the left of the pairwise comparison table. Table 8 is the result of comparison between stakeholder's criteria.

Intensity of Importance	Definition
1	Equal Importance
2	Moderate Importance
3	Strong Importance
4	Very Strong Importance
5	Extreme Importance

Table 7 Pair-wise scoring scale

	Calibrate power sensors	Reliability	Raw data	System flexibility	System efficiency	Maintainability	Vendor Support	Easy to use	Affordability	Weights
Calibrate power sensors	1.00	0.50	3.00	4.00	4.00	5.00	3.00	5.00	5.00	0.2196
Reliability	2.00	1.00	4.00	5.00	5.00	5.00	4.00	5.00	5.00	0.2959
Raw data analysis	0.33	0.25	1.00	2.00	2.00	4.00	1.00	3.00	5.00	0.1116
System flexibility	0.25	0.20	0.50	1.00	1.00	3.00	0.50	2.00	5.00	0.0744
System efficiency	0.25	0.20	0.50	1.00	1.00	3.00	0.50	2.00	5.00	0.0744
Maintainability	0.20	0.20	0.25	0.33	0.33	1.00	0.25	0.50	3.00	0.0372
Vendor Support	0.33	0.25	1.00	2.00	2.00	4.00	1.00	3.00	5.00	0.1116
Easy to use	0.20	0.20	0.33	0.50	0.50	2.00	0.33	1.00	4.00	0.0508
Affordability	0.20	0.20	0.20	0.20	0.20	0.33	0.20	0.25	1.00	0.0245

Table 8 Pair-wise comparison

Figure 17 below are stakeholder's criteria with their respective weights represented in percentages. It gives a visual picture of the important criteria that supports the calibration system as it is refined.

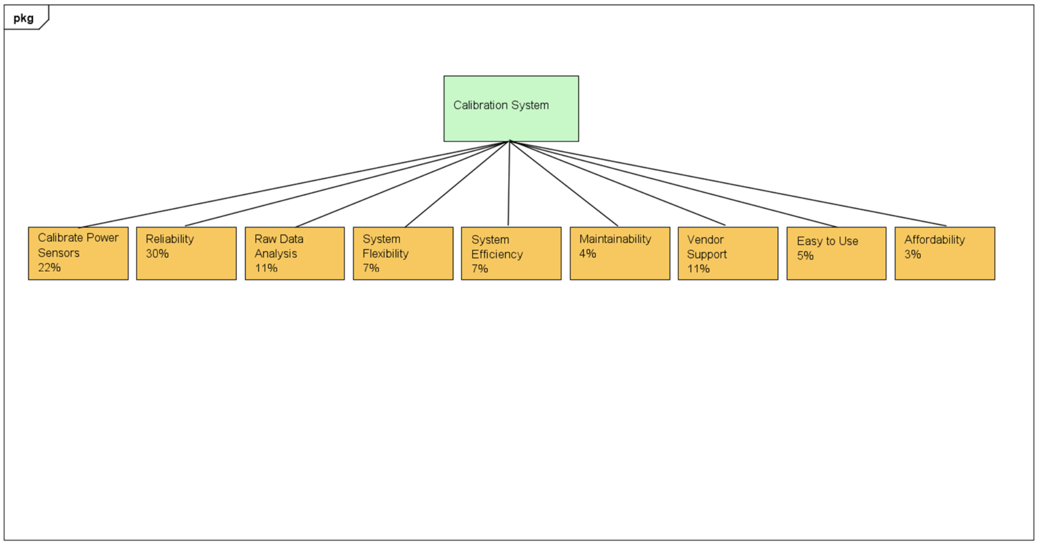

Figure 17 Weighted Criteria

4.7.2 Utility Curves

Utility curves are scoring scales based on stakeholder's requirements and "represent value for a particular stakeholder or group of stakeholders with common values." (Technology, 2014). For this project it is important to accurately define utility curves because it is a foundational step to accurately evaluate alternative systems from an unbiased point of view. Stakeholders have 9 requirements for the development of the power sensor system along with 9 utility curves and its utility definition referenced in Appendix B.

4.7.3 Alternative System Evaluation

The five system concepts and nine criteria were placed in a table so the stakeholder could understand and visualize the different system specifications against the criteria. Criteria with known values such as calibrate sensors to manufacturer's specifications, system reliability, raw data analysis, system flexibility, and system efficiency are factual values for the capability of each system. According to the utility curves descriptions system maintainability, system supportability, easy to operate, and system affordability are subjective and are an expected value based on the perception of the stakeholders experience to perform the task. Table 9 is populated with values of each system.

Power Sensor Calibration System	System Concept #1	System Concept #2	System Concept #3	System Concept #4	System Concept #5
CRITERIA	Sandia's Custom Calibration System	Tegam	Keysite	CalLab Solutions	External Calibration Site
Calibrate sensors to manufacturer's specifications	100%	80%	50%	80%	50%
System reliability	99% up time	90% up time	99% up time	90% up time	90% up time
Raw data analysis	Source code; raw data; tolerance analysis	Raw data; tolerance analysis	Partial data availability	Complete data availability	No raw data availability
System flexibility	Accepts all certified standards.	Accepts 90% certified standards	Accepts <40% certified standards	Accepts 90% certified standards	Accepts all certified standards.
System efficiency	Within 6 hours	Within 2-4 hours	Within 1 day	Within 1 day	>2 days
System maintainability	1 Day	5 Hours	7 Hours	7 Hours	2 hours
System supportability	Within 1 day	Within 6 hours	Within 2-4 hours	Within 1 day	Within 2-4 hours
Easy to operate	Very Good	Exceptional	Satisfactory	Very Good	Exceptional
System affordability	$50,001-$75,000	$50,001-$75,000	$100,001-$150,000	$75,001-$100,000	$75,001-$100,000

Table 9 System Comparison

After the stakeholders reviewed the information presented in Table 9, they proceeded to assign a utility value based on the utility curves presented in **Error! Reference source not found.** with the following results:

Power Sensor Calibration System	System Concept #1	System Concept #2	System Concept #3	System Concept #4	System Concept #5
CRITERIA	Sandia's Custom Calibration System	Tegam	Keysite	CalLab Solutions	External Calibration Site
Calibrate sensors to manufacturer's specifications	5	4	3	4	3
System reliability	4	3	4	3	3
Raw data analysis	5	4	2	3	1
System flexibility	5	4	1	4	5
System efficiency	4	5	3	3	1
System maintainability	3	4	3	3	5
System supportability	3	4	5	3	5
Easy to operate	4	5	3	4	5
System affordability	4	4	2	3	3

Table 10 Comparison Results

4.7.4 Recommendation

The weights for each requirement from the pairwise comparison and the comparison results from table 10 were used to determine a final decision. Criteria were listed with its respective weight value from the pairwise comparison. System concepts were listed with its respective value from the comparison results. Each criterion's weight value was multiplied by the system concepts comparison value. Finally, the results for each system concept were tallied for a final system recommendation. The trade study analysis in Table 11 illustrates the results for each system concept.

Power Sensor Calibration System	Weight	System Concept #1		System Concept #2		System Concept #3		System Concept #4		System Concept #5	
CRITERIA		Sandia's Custom Calibration System		Tegam		Keysite		CalLab Solutions		External Calibration Site	
Calibrate sensors to manufacturer's specifications	0.2196	5	1.098	4	0.8784	3	0.6588	4	0.8784	3	0.6588
System reliability	0.2959	4	1.1836	3	0.8877	4	1.1836	3	0.8877	3	0.8877
Raw data analysis	0.1116	5	0.558	4	0.4464	2	0.2232	3	0.3348	1	0.1116
System flexibility	0.0744	5	0.372	4	0.2976	1	0.0744	4	0.2976	5	0.372
System efficiency	0.0744	4	0.2976	5	0.372	3	0.2232	3	0.2232	1	0.0744
System maintainability	0.0372	3	0.1116	4	0.1488	3	0.1116	3	0.1116	5	0.186
System supportability	0.1116	3	0.3348	4	0.4464	5	0.558	3	0.3348	5	0.558
Easy to operate	0.0508	4	0.2032	5	0.254	3	0.1524	4	0.2032	5	0.254
System affordability	0.0245	4	0.098	4	0.098	2	0.049	3	0.0735	3	0.0735
			4.2568		3.8293		3.2342		3.3448		3.176

Table 11 Trade study analysis

Based on stakeholder's priority of operations, system concept #1 is the system of choice that meets PSL's need for an RF power sensor calibration system. The system meets stakeholder's criteria to:

- Calibrate sensors to manufacturers specifications
- Analyze data to determine tolerances for calibrated equipment
- Flexibility to choose system components based on PSL's availability
- Efficiently use system resources improving equipment turnaround time
- Maintainability
- Supportability
- Easily operate software to successfully calibrate equipment
- Affordable

4.8 Risk Analysis of Selected System

Calibration technicians at the PSL have been in the business on an average of 25 years. They are extremely experienced and used to calibrating equipment manually and may not be receptive to a new structured methodology to developing calibration systems and calibrating equipment. The first risk identified is adversity to change. A mindset change has to happen where they can accept that training is needed to learn and understand the concept of SE and its importance to the continued success of the PSL. The mitigation strategy is to provide in depth SE training classes and SE staff assistance. As technicians learn and apply the concept, the more effective they will be in identifying the need, analyzing requirements, and applying MBSE to a future need. Learning and applying SE concepts will technologically future proof the PSL providing calibration technician's job security at Sandia National Laboratories.

The second risk is the possibility of damaged standards during shipment for its yearly calibration. It is SNL's policy that standards will be calibrated yearly by an authorized source such as NIST to ensure accuracy of data measurement results. The current process is to pack the standard in a hard-shell case and send it using FedEx or UPS. The PSL has no control over handling of the standard once it is shipped. Standards are insured, however, when damages occur making a claim is time consuming delaying data availability for stakeholders. The standard can be replaced however it would have to go through the uncertainty analysis and verification process for every output which is additional downtime for the system. The mitigation for this risk is to form a business partnership with standards manufacturers to perform yearly onsite calibrations. The expected system downtime for the yearly onsite calibration is 7 days.

Finally, the third risk identified is System downtime for routine maintenance. Routine maintenance is necessary in order to keep standards operating properly between calibration cycles. Calibration standards identifies if voltage, resistance, frequency measurements are drifting. Since calibration systems are “one of a kind” to Sandia, a maintenance procedure would be developed by the calibration engineer for the calibration technician. Initial routine calibration time is expected to be 3 hours which would decrease to one hour once proficiency is achieved.

A risk assessment matrix is used to illustrate the impact is shown in Table 13. The consequence and likelihood of the potential risk may be reported as negligible/not likely, low, moderate, high and extreme/expected with the colors green for low risk, yellow for moderate risk, and red for high risk. The number in each box represents the risk level which is the result of the likelihood multiplied by the consequence.

Likelihood		Consequence: Negligible 1	Low 2	Moderate 3	High 4	Extreme 5
Expected	5	**5**	**10**	**15**	**20**	**25**
High	4	4	8	12	16	20
Moderate	3	3	6	9	12	15
Low	2	2	4	6	8	10
Not Likely	1	1	2	3	4	5

Table 12 Risk Assessment Matrix

Consequence and likelihood levels scoring scale are listed in Table 13 and Table 14. The consequence table describes stakeholder's emotion and frustration and is directly correlated with system performance.

Consequence	Level	System Result
Extreme	5	System is nonoperational for 30 days or more. Stakeholders are unhappy with the system.
High	4	System is nonoperational for 15 days or more. Stakeholders are concerned about the system.
Moderate	3	System is nonoperational for 7 days or more. Acceptable by stakeholders.
Low	2	System is nonoperational for 1 day. Expected by stakeholders.
Negligible	1	System is nonoperational for 1 hour. Not of concern to stakeholders.

Table 13 Consequence Table

System occurrence description in Table 14 describes the frequency of risks occurring during the lifetime of the system.

Likelihood	Level	System Occurrence Description
Expected	5	Continuously occurring in the lifetime of the system.
High	4	Will occur frequently in the lifetime of the system.
Moderate	3	Will occur several times in the lifetime of the system.
Low	2	Reasonably expected to occur in the lifetime of the system.
Not Likely	1	Unlikely to occur but possible in the lifetime of the system.

Table 14 Likelihood Table

The risks were presented to stakeholders for evaluation. After careful consideration of all risks presented, stakeholders scored each risk with the likelihood of occurrence and consequence if it occurred using the consequence and likelihood tables as a scoring scale. The two numbers were multiplied for a final risk score which was compared against the risk matrix to assess the level of risk.

After risks were scored, mitigation strategies for every risk were presented to stakeholders. Using the consequence and likelihood table, they were asked to score each strategy. The two numbers were multiplied for a final score. The score was compared against the risk matrix to assess the level of mitigation. The Risk Log below is the final result for risk and mitigation strategies.

Risk	Likelihood	Consequence	Score	Mitigation Strategy	Likelihood	Consequence	Score
Staff lack of experience with SE concepts.	**4**	**5**	20	Provide training classes and engineering support.	**3**	**2**	6
Damaged standards during shipment for yearly calibration.	**3**	**4**	12	Form a business partnership with standards manufacturers to perform yearly onsite calibrations.	**3**	**3**	9
System maintenance downtime.	**5**	**4**	20	Develop and standardize a best maintenance practice for technicians.	**5**	**2**	10

Table 15 Risk Log

5. FUTURE ACTIVITIES FOR THE PSL

Future activities for the PSL to complete this project consist of two phases: integrating and implementing MBSE concepts and PSL's calibration system validation process. The first phase is integrating and implementing MBSE concepts. The lack of structure for calibration system development is the driving force for implementing SE concepts to provide a structure to develop successful calibration systems to meet customer demands. PSL management, Team Leads, and Engineering staff will have to be on board with full support and understanding the applicability of the model presented in figure 5. Further analysis of the model can be expanded to include reliability and supportability of complex calibration systems that are software driven. Logistics analysis should also be taken into consideration to provide stakeholders a clear expectation of the systems capabilities. It is possible to expedite the implementation of SE by consulting with SE subject matte experts. Sandia National Laboratories has a vast network of SE knowledge and access to educational institutions for training such as Stevens Institute of Technology. Training can be conducted onsite for deeper analysis of concepts introduced in this project.

The second phase consists of the calibration system validation process. The system validation process is conducted by the department manager, engineering staff, technologists, and other SME's that had a significant role in developing the new system. All systems at the PSL must be verified and approved by the department manager before calibration certifications or reports can be issued using any new system (Burton, 2013). The validation process is rigorous and consists of an approval checklist that includes the following areas:

- Theory of operation
- Uncertainty analysis
- System certification procedure and controls
- Calibration procedure for equipment to be calibrated
- Software
- Safety of the system
- Environmental impacts the new system may have on PSL's National Environmental Protection Act document.

The completed approval checklist is reviewed and maintained by the department's quality coordinator. Any noted action items or comments are addressed and resolved before signoff and before the system is placed into service. When action items are resolved the project member discusses the items with the Department Manager, who then initials and dates the item under the Completed column on the checklist. The system is placed into service and periodically reviewed every 5 years.

6. CONCLUSIONS AND ALTERNATIVE RECOMMENDATION

The PSL was in need of a framework for development and deployment of successful calibration systems. The lack of knowledge and full implementation of SE to the development of complex calibration systems stressed the PSL's ability to meet customer's needs in a timely and cost effective manner. The complexity of the problem created an opportunity to apply SE principles to find solutions that meet the challenge without outsourcing equipment while improving customer satisfaction. SE principles were introduced as a guide to provide a framework of best practices by applying System Thinking, Trade Study Analysis process, and System Architecture and Design to the development of a RF calibration system. MBSE was the formalized application to effectively communicate requirements and system design for development and implementation that meets the stakeholder's needs. Based on the case study, it was demonstrated that SE principles has the opportunity to have a positive organizational and business impact by providing structure in the development of successful calibration systems increasing onsite calibration productivity while improving calibration turnaround times and customer satisfaction.

The recommendation for the PSL is the application of Model Based Systems Engineering (MBSE) to the development of calibration systems and implement SE concepts such as systems thinking, trade study analysis, and system architecture and design. System thinking as mentioned in section **Error! Reference source not found.** provides principles that give understanding on how system components interact with each other for a systems approach to solutions. In section **Error! Reference source not found.**, system architecture and design is where system requirements and system concepts come together to develop system architectures to reassure that stakeholder requirements were accurately captured. Trade study analysis further refines and develops the system giving confidence all information has been accounted for a final system decision.

Successful implementation of MBSE requires a mindset change and full support of all involved stakeholders. PSL management, Team Leads, and Engineering staff will have to be on board with full support and understanding of the applicability of the various models to system development. Prerequisites to employ an MBSE approach are:

- PSL must make available to all the engineering staff a basic level of training in the MBSE processes so that they understand the value of the models and in how to read MBSE artifacts so that they can interpret information provided from the MBSE process.
- An investment in basic MBSE training with a moderate skill in employing MBSE tools and techniques will benefit the PSL to develop a skill that facilitates the implementation of successful systems.
- Proper definitions of MBSE model management processes to create, update, and maintain MBSE models through the systems lifecycle.
- Investment in MBSE tools and procedures with full scale implementation and standardization.

As MBSE provides structure it will enable rapid development and deployment of successful calibration systems that meet the needs of the PSL. The PSL would also benefit from MBSE because it paves the way to:

- Increase the ability to manage system complexity by enabling a system model to be viewed from multiple perspectives, and to analyze the impact of changes.
- Improve product quality by providing an unambiguous and precise model of the system that can be evaluated for consistency, correctness, and completeness.
- Enhance knowledge capture and reuse of the information in more standardized ways and leveraging built in abstraction mechanisms inherent in model driven approaches.
- Improve the ability to teach and learn systems engineering fundamentals by providing a clear and unambiguous representation of the concepts. (Griego & Sampson, 2009)

6.1 Alternative Recommendation

The alternative system development model verifies the first three steps and applies systems thinking concepts up front as shown in Figure 18. The alternative development model is setup to verify stakeholders needs against concept of operations and verify concept of operations against system architecture. The two verification loops are repeated as many times as necessary resulting in clear understanding of stakeholder needs, detailed representation of concept of operations, and accurate system architecture and design.

System thinking is applied to concept of operations and system architecture and design. The purpose of systems thinking to concept of operations is to understand system behaviors as the system evolves through the verification loop process. The purpose of system thinking to system architecture and design is to detect unintended consequences of component interaction as the system evolves through verification loop process. The alternative development model integrates system thinking early on to the development process as a means to understand the system as a whole as the system is developed

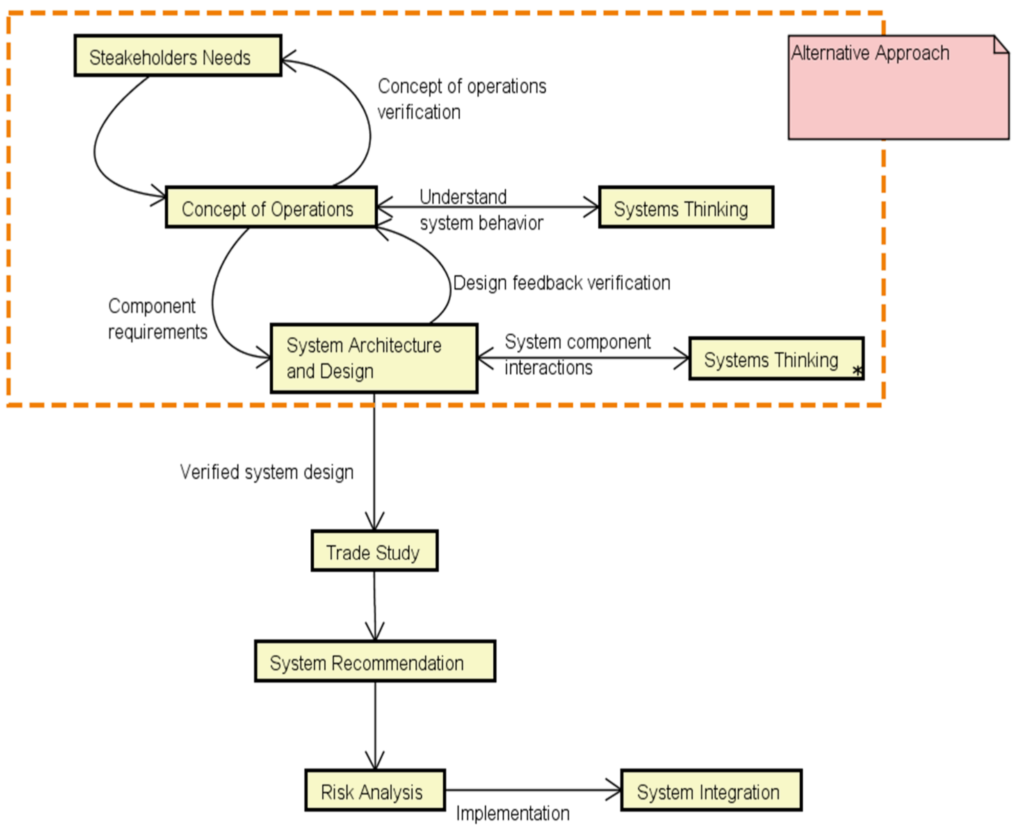

Figure 18 Alternative SE System Development Model

from concept to realization.

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APPENDIX A. ACTIVE POWER SENSORS MANAGED BY THE ELECTRICAL LAB AS OF 11 MARCH 2015

Manufacturer	Model
AGILENT	E9304A
AGILENT	E9304A OPT. H18
AGILENT	8482A
AGILENT	8481A
AGILENT	E4412A
AGILENT	8481A
AGILENT	8487A
AGILENT	E4413A
AGILENT	8481A
AGILENT	E9304A OPT. H18
AGILENT	E9304A OPT. H18
AGILENT	8481A
AGILENT	8487A
AGILENT	N8487A
AGILENT	N8487A
AGILENT	E9304A
AGILENT	E9304A
AGILENT	E9304A
AGILENT	N8486AR
AGILENT	E9304A
AGILENT	E9304A
AGILENT	E9300A
AGILENT	8481B
AGILENT	E9300A
AGILENT	E9300A
AGILENT	U2001A
AGILENT	U2001A
AGILENT	E9304A OPT. H18
AGILENT	E9304A OPT. H18
AGILENT	E9300A
AGILENT	E9300A
AGILENT	8482A
AGILENT	E4413A
AGILENT	8481B
AGILENT	E9325A
AGILENT	N1922A
AGILENT	E9327A
AGILENT	8487D
AGILENT	N1922A

Manufacturer	Model
AGILENT	8481B
AGILENT	U2001A
AGILENT	U2001A
AGILENT	U2001A
AGILENT	U2001A
AGILENT	E9304A
AGILENT	U2001A
AGILENT	U2001A
AGILENT	U2001A
AGILENT	U2001A
AGILENT	E4412A
AGILENT	E4412A
AGILENT	E9304A
AGILENT	U2001A
AGILENT	E9304A OPT. H18
AGILENT	E4413A
GIGTRNIC	80301A
GIGTRNIC	80301A
GIGTRNIC	80301A
GIGTRNIC	80314A
GIGTRNIC	80301A POWER SENSOR
GIGTRNIC	80314A
GIGTRNIC	80301A
GIGTRNIC	80301A
GIGTRNIC	80314A POWER SENSOR
GIGTRNIC	80314A POWER SENSOR
GIGTRNIC	80314A POWER SENSOR
GIGTRNIC	80314A POWER SENSOR
GIGTRNIC	80304A POWER SENSOR
GIGTRNIC	80301A POWER SENSOR
GIGTRNIC	80314A POWER SENSOR
GIGTRNIC	80304A POWER SENSOR
GIGTRNIC	80314A POWER SENSOR
GIGTRNIC	80304A POWER SENSOR
GIGTRNIC	80304A POWER SENSOR

APPENDIX B. UTILITY CURVES

Calibrate Power Sensors	Rating
100%	5
71% - 99%	4
41% - 70%	3
11% - 40%	2
<10%	1

Calibrate power Sensors utility curve is based on the system's ability to accurately calibrate different model types of power sensors used by the PSL's customers.

System Reliability	Rating
99.99% up time	5
99% up time	4
90% up time	3
80% up time	2
<70% up time	1

System reliability utility curve is based on mean time between failures (MTBF) and the system's ability to calibrate equipment for an extended period of time.

Raw Data Analysis	Rating
Source code/raw data/tolerance analysis	5
Raw data/tolerance analysis	4
Complete data availability	3
Partial data availability	2
No raw data availability	1

Raw data analysis is the PSL's ability to access raw data for further analysis of equipment.

System Flexibility	Rating
Accepts all certified standards.	5
Accepts 90% certified standards	4
Accepts 75% certified standards	3
Accepts 50% certified standards	2
Accepts <40% certified standards	1

System flexibility is calibration system ability to use standards from different manufacturers. A flexible system maximizes resource availability for the PSL.

System Efficiency	Rating
Within 2-4 hours	5
Within 6 hours	4
Within 1 day	3
Within 2 days	2
>2 days	1

System efficiency is the amount of time the calibration system takes to calibrate equipment. The PSL has a 3 day turnaround time goal to calibrate and return equipment to the customer.

System Maintainability	Rating
1-3 Hours	5
3-6 Hours	4
1 day	3
2-3 days	2
4-5 days	1

System maintainability refers to the amount of time it takes the system to be restored to operational status after a failure occurs or after required maintenance.

System Supportability	Rating
Within 2-4 hours	5
Within 6 hours	4
Within 1 day	3
Within 2 days	2
>2 days	1

System supportability is the amount of time it takes the vendor to provide training, support, and answer questions to minimize system downtime.

Easy to Operate	Rating
Exceptional	5
Very Good	4
Satisfactory	3
Marginal	2
Poor	1

Easy to use refers to the daily operations of the system. This utility curve is subjective and based on PSL staff experience.

System Affordability	Rating
<$50,000	5
$50,001-$75,000	4
$75,001-$100,000	3
$100,001-$150,000	2
>$150,001	1

Affordability is the overall cost of the system including maintenance, training, and upgrades as needed.

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