Systems Architecture

This section of the DSA Roadmap report describes the multiple aspects that constitute systems architecture as described by the Department of Defense (DOD) in its architecture framework. The DOD framework is designed to create interconnectivity and interoperability between air, land and sea systems from multiple vendors.

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Introduction

Systems Architecture is a method for describing how all the systems, sub-systems and components in a complex collection of systems function coherently to deliver a defined result according to requirements. The Architectural Framework method from the DoD provides visualization for stakeholders' concerns organized by various 'views' to describe the Systems Architecture of complex systems. These views are used for visualizing, understanding and describing aspects of the broad scope and complexities of an architecture description. The Architecture Framework is especially suited to large systems with complex integration and interoperability challenges, such as those that exist in both aerospace and drilling systems. These views offer overview and details for specific stakeholders within a domain, and for how interactions with other domains in the stakeholders' system will operate.

This section of the DSA Roadmap report proposes an industry model that offers significant advantages for the advancement of Drilling Systems Automation (DSA). The model combines many of the aspects required for the application of DSA by providing a method by which these various aspects may interrelate. This model is intended as a tool to be maintained by a standards organization for controlled updates through continuing collaboration as technology and DSA solutions advance.

Systems Architecture Value

Systems architecture is particularly important in highly interdependent, complex systems where multiple companies participate jointly.

Systems Architecture (SA) is a foundation for an industry solution to many key aspects of DSA, including interoperability and identification of Systems of Interest (SoI). The former provides multiple companies the ability to cooperate on complex projects and to deliver a unified solution. The latter identifies subsystems to which improvements to sensors, data flow, processing and control delivers value.
Advanced technology industries—particularly automotive, aerospace and defense-based industries—have developed architectural frameworks based on a theme of "collaborate on standards and compete on innovation." DSA can emulate this theme to increase the rate at which this technology application is adopted. The system's Reference Architecture provides a foundation for developing the basis for collaboration among all the entities involved in drilling and completing wells. The drilling industry will be slow to advance DSA application without a common approach to systems architecture at the Reference Architecture level. If the industry fails to develop the means for various parties to collaborate across a DSA project, the primary

advancement will occur only for companies that own or have access to all the components in the DSA system.

Industry Evolution

In 2019, the industry is applying applications to semi automate specific processes in a bottom-up approach. One major service company is developing a full systems approach and has purchased multiple companies to complete a portfolio of systems. This solution is in the development phase. Two operators who pursued drilling automation strategies have redirected their efforts; one company is focusing on acquiring and processing data and the other licensed its development to other applicators because the effort and cost to connect to multiple rig machine control systems proved prohibitive. The latter company continues to develop some automated subsystems, particularly those related to geosteering.

The industry appears unlikely to adopt standards that will quickly enable interoperability. In 2019, interoperability is creeping forward as and where it serves a competitive advantage purpose to keep customers under contract. The bottom-up approach carries numerous risks to implementation that result from the lack of oversight of the relationship between automated subsystems. The bottom-up approach is failing also to strategically address the change in human competencies and the related training (see Human Systems Integration section).

Selection of an Architectural Method

The USA DoD have recognized the importance of systems architecture as a foundation to complex, interdependent system development and published a methodology to develop systems architecture.[1] This is captured in DOD Architecture Framework (DoDAF), which also has been adopted by NATO as its Architectural Framework. Full development of systems architecture is a major undertaking. Industry application can be achieved through a hierarchical development of Reference Architecture, Pattern Architecture and Solutions Architecture. This DSA Roadmap focuses on the development and progression of Reference Architecture to a high-level industry-applicable architecture that guides a common industry approach for consistent adoption by projects to manifest the highest value.

Implementing a Systems Architecture

Department of Defense Architectural Framework (DoDAF)

The Department of Defense Architectural Framework, v2.02, 31 January 2015 Introduction describes the DoDAF as “the overarching, comprehensive framework and conceptual model for architectural descriptions developed within the DoD. The DoDAF is the structure for organizing architecture concepts, principles, assumptions, and terminology about operations and solutions into meaningful and consistent patterns to satisfy specific DoD purposes. The DoDAF offers guidance, principles, and direction on communicating business and mission needs and capabilities to managers, architects, analysts, and developers who are responsible for developing and building the necessary systems, services, applications, and infrastructure to meet stakeholder needs and to manage their expectations.” [1]

“This framework helps DoD managers at all levels make effective decisions by sharing information across the Department, Joint Capability Areas (JCAs), missions, components, and programs. The DoDAF focuses on the collection, presentation, and sharing of architectural data as information required by DoD decision makers, rather than on developing individual models. Architects may use the standard models described in this Volume I and specified in Volume II to obtain and visualize architecture data. However, the framework also allows architects to build other, fit-for-purpose (FFP) products for an architectural description.”[1,2]

The challenges faced by highly complex DoD projects that require interoperability and must perform in uncertain environments that are much like those faced by drilling oil and gas wells. This similarity makes the DoDAF approach to systems architecture both viable and valuable for DSA architectures by providing a mechanism for understanding and managing complexity.

DoDAF Eight View Points

The eight viewpoints of DoDAF provide a comprehensive means to develop an architecture.

1. The All Viewpoint describes the overarching aspects of architecture context that relate to all viewpoints.
2. The Systems Viewpoint is the design for solutions articulating the systems, their composition, interconnectivity, and context providing for, or supporting operational and capability functions.
3. The Capability Viewpoint articulates the capability requirements, the delivery timing and the deployed capability.
4. The Operational Viewpoint includes the operational scenarios, activities, and requirements that support capabilities.
5. The Data and Information Viewpoint articulates the data relationships and alignment structures in the architecture content for the capability and operational requirements, system engineering processes and systems and services.

6. The Project Viewpoint describes the relationships between operational and capability requirements and the various projects being implemented. The Project Viewpoint also details dependencies among capability and operational requirements, system engineering processes, systems design and services design.
7. The Services Viewpoint is the design for solutions articulating the Performers, Activities, Services and their Exchanges, providing for or supporting operational and capability functions.
8. The Standards Viewpoint articulates the applicable operational, business, technical, and industry policies, standards, guidance, constraints and forecasts that apply to capability and operational requirements, system engineering processes and systems and services.

In a hierarchical approach to architecture, not all views are relevant at the highest level.

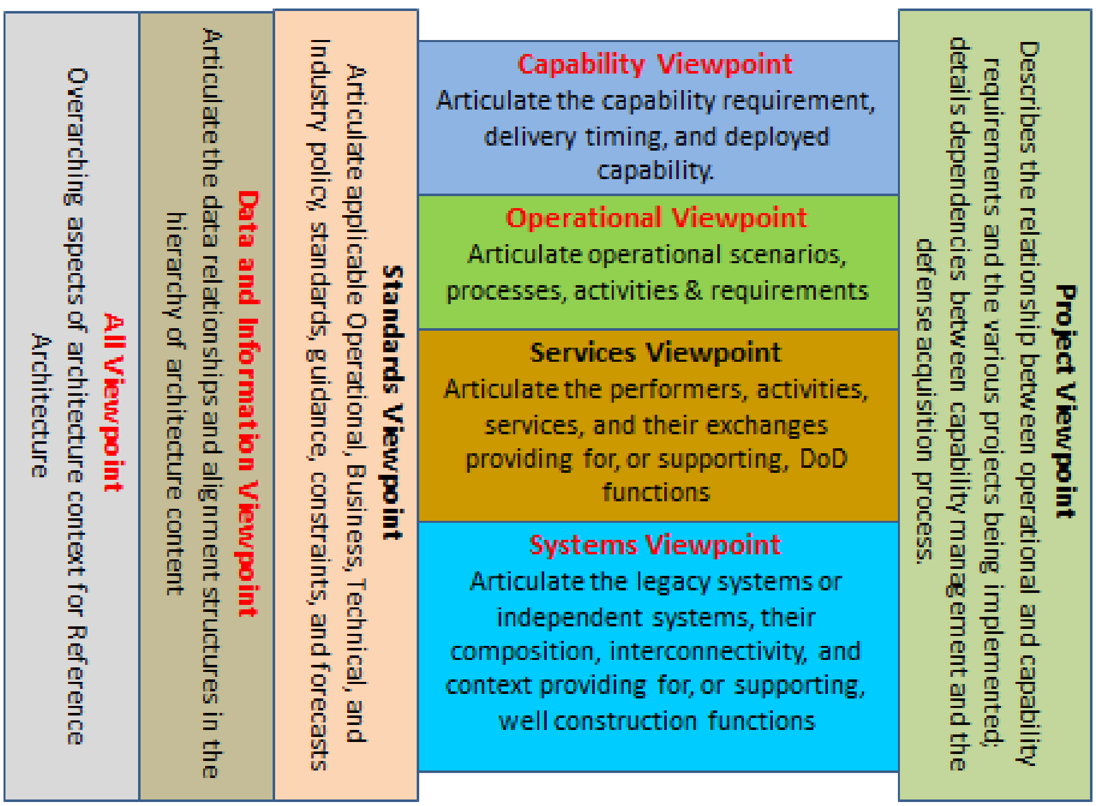

Figure 1-Diagram of DoDAF eight viewpoints

For the DSA Roadmap we have selected the following views as relevant and applicable to defining the Reference Architecture:

- All Viewpoints
- Systems Viewpoint –overall Systems of Systems and the focused Systems of Interest
- Capability and Operational Viewpoints combined to cover the functional view
- Data and Information viewpoint.

Other viewpoints are covered under other circumstances including Pattern and Solutions Architectures:

Project Viewpoint is particular to a Solutions Architecture

- Services viewpoint is particular to Solutions Architecture
- Standards viewpoint is covered in the standards section as to applicable standards and further detail is specific to solutions architecture.

Drilling Systems Adaptation

Systems Architecture can be described in a hierarchical manner from an industry approach (Reference Architecture) to a project solution (Solutions Architecture). The breadth of options for rig type and well type warrant an additional level of Pattern Architecture between Reference and Solutions Architecture. Patterns are models of architecture representations at a level of generality that provides some degree of reuse, which enables improved connectivity between Reference Architecture and Solutions Architecture.

The three levels of architectures offer a range from cooperation to competition as Reference Architecture—industry cooperation for standards, Pattern Architecture—distinctions within the reference architecture for industry benefit, and Solutions Architecture—innovation and competitive advantage for companies.

Reference Architecture

Reference Architecture is an authoritative source of information about a specific subject area that guides and constrains the instantiations of multiple architectures and solutions.[3]

Reference Architecture improves the industry's ability to create products, product lines and product portfolios by:

- Managing synergy

- Providing guidance, e.g. architecture principles, best practices
- Providing an architecture baseline and an architecture blueprint
- Capturing and sharing (architectural) patterns.

Achieving interoperability between many different and evolving systems is critical for success of industry wide DSA. Interoperability drives the usability, performance and dependability of user level applications. Reference Architectures is designed to improve interoperability by:

- Delivering a common approach to the architectural definition for DSA across all operations
- Providing a common approach to Systems of Interest and their connectivity that delivers DSA
- Offering a framework for companies to enter DSA in a predictable manner
- Enabling compatibility, upgrade and interchangeability.

Reference Architecture offers the opportunity to decrease integration cost and time to participants in the application of DSA by providing a common view of the DSA framework for application of automation.

Reference Architecture is considered an industry asset that:

- Provides common language for the various stakeholders
- Provides consistency of implementation of technology to solve problems
- Supports the validation of solutions against proven Reference Architecture
- Encourages adherence to common standards, specifications and patterns.

Pattern Architecture

Patterns show how artifacts may be organized and related from repeated use. They are typically low to mid-level tabular, structural, behavioral, or graphic model abstractions that focus on interaction of the artifacts.[3] Patterns undergo change most often as new pattern concepts are discovered and emerge from the solutions architectures. Patterns may be conveyed through various means, such as activity, process and behavioral models. It is important to identify a pattern and describe it with enough detail to be understood clearly and used appropriately. The potential benefits of architectural patterns include:

- Enabling improved communication between stakeholders
- Facilitating the application of sound architectural concepts and implementations
- Multiple implementations that lead to standardization.[4]

Solutions Architecture

DoD Reference Architecture Description defines Solution Architecture as a framework or structure that portrays the relationships among all the elements of something that answers a problem.[3] It describes the fundamental organization of a system embodied in its components, their relationships with each other and the environment, and the principles governing system design and evolution. Solution architecture instantiations are guided and constrained by all or part of a Reference Architecture in which the generalized and logical abstract elements of the Reference Architecture are replaced by real world physical elements according to specific rules, principles, standards and specifications.

Drilling Systems Automation Systems Architecture

Approach to a Hierarchy of Systems Architectures

Systems architecture can be described in a hierarchical manner from a broad industry architecture termed the Reference Architecture down though "Pattern Architectures" and "Solution Architectures." Reference Architecture captures the essence of existing architectures, and the vision of future needs and evolution to provide guidance in developing new system architectures. A Reference Architecture facilitates a shared understanding across multiple products, organizations and disciplines about current architecture(s) and future directions that enable interoperability. Proven architectures of past and existing products are transformed in a Reference Architecture. However, the purpose of the Reference Architecture is future oriented, in that it provides guidance for future implementations, as in the DSA Roadmap.

DoD defines Reference Architecture as an "authoritative source of information about a specific subject area that guides and constrains the instantiations of multiple architectures and solutions." [3] Reference Architecture provides the framework for the industry to develop collaborative solutions than can be made interoperable at the solutions level. Without a common Reference Architecture, the interoperability at the solutions level would not be holistic.

While the Reference Architecture provides a global industry orientation for the relationships of various activities that combine to deliver a drilled and completed well, it does not provide the details that are required for a specific project. However, the Reference Architecture articulates the high-level framework the industry ought to follow for interoperability within a specific project.

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Cloutier et al, in a Systems Architecture Forum, noted that in all domains, two simultaneous emerging trends drive the development of a Reference Architecture:

- Increasing complexity, scope and size of the system of interest, its context and the organizations creating the system
- Increasing dynamics and integration that results in shorter time to market, more interoperability, and rapid changes and adaptations in the field. [4]

These trends occur in DSA and provide further evidence of the value of the industry adopting a Reference Architecture.

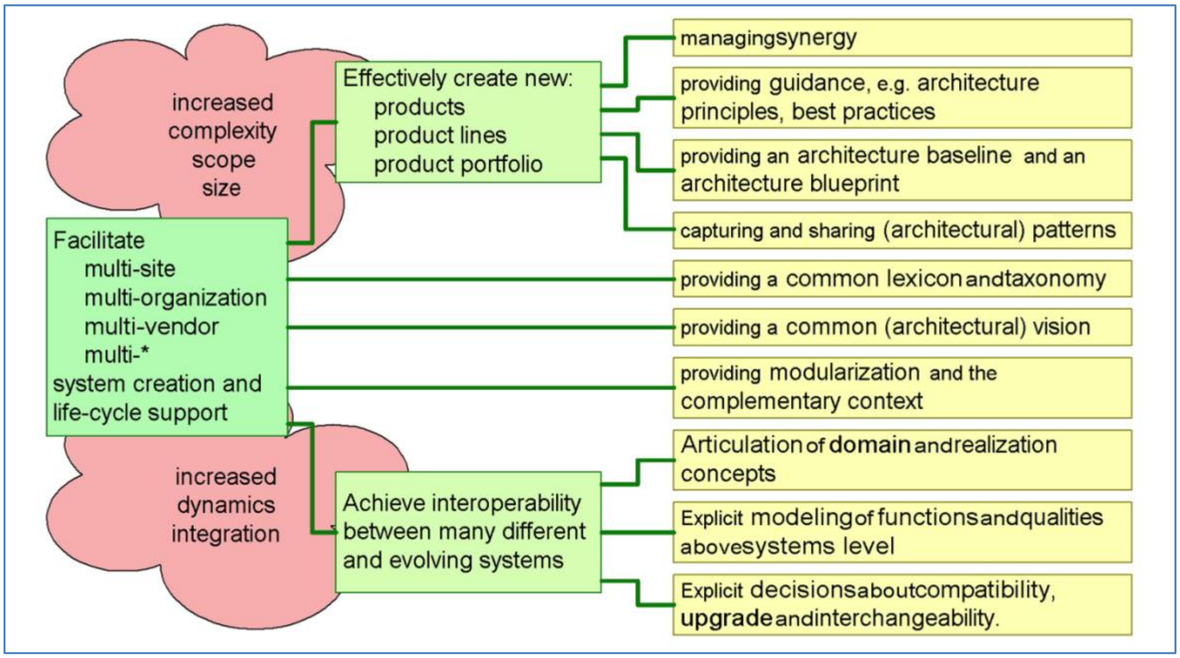

Figure 2- Cloutier Et al - Graph of objectives of Reference Architectures

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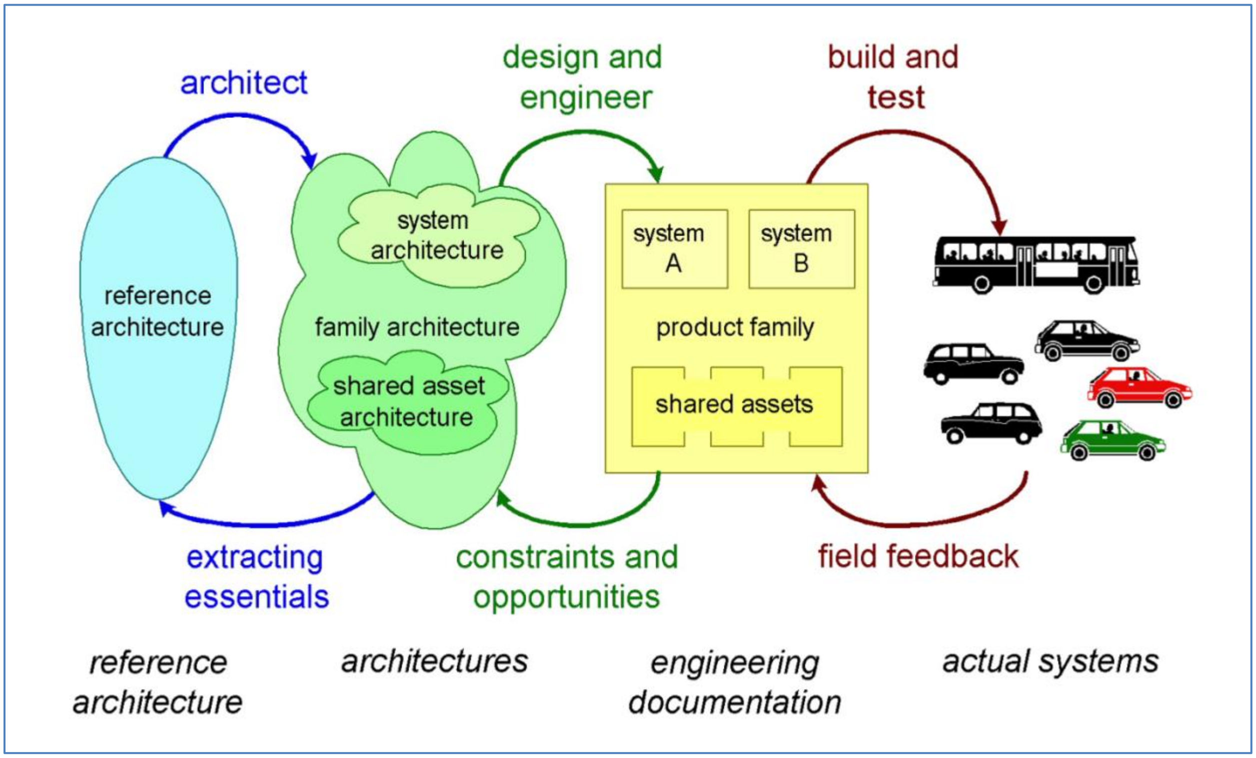


Figure 3- Reference Architectures are very abstract. In several instantiation steps a Reference Architecture is transformed into an actual architecture[4]

The DSA Roadmap recognizes three levels of architecture from reference, through pattern, to solutions as described below.

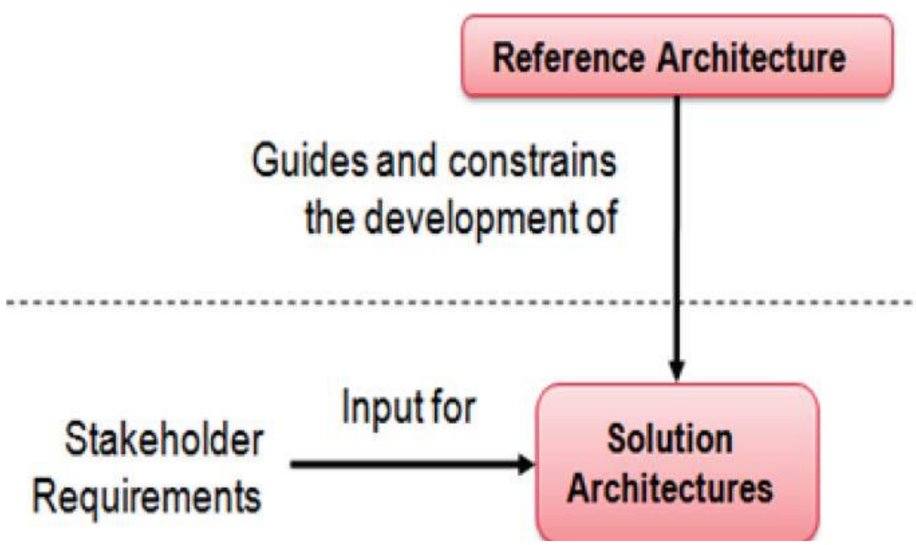


Figure 4- DoD Relationship Reference Architecture to Solution Architecture

Patterns are models of architecture representations at a level of generality that provides some degree of reuse. DOD defines Solution Architecture as a framework or structure that portrays the relationships among all the elements of something that answers a problem.[3] Solution Architecture describes the fundamental organization of a system, embodied in its components, their relationships with each other and the environment, and the principles governing its design and evolution. Solution architecture instantiations are guided and constrained by all or part of a Reference Architecture in which the generalized and logical abstract elements of the Reference Architecture are replaced by real-world physical elements.

The roadmap envisages that the Reference Architecture is an industry common architecture that grounds Pattern Architectures and Solutions Architectures. Solutions Architecture is the detailed systems architecture for specific drilling and completions operations. It is the level of detailed architecture that delivers the wells. This is an area for innovation and competitive advantage that does not form part of the roadmap except to position it relative to Reference Architecture. Lessons learned and knowledge gained at the Solutions Architecture detailed level can be fed back to drive developments and improvements in the Pattern Architecture which in turn can be captured in the Reference Architecture to steer the industry.

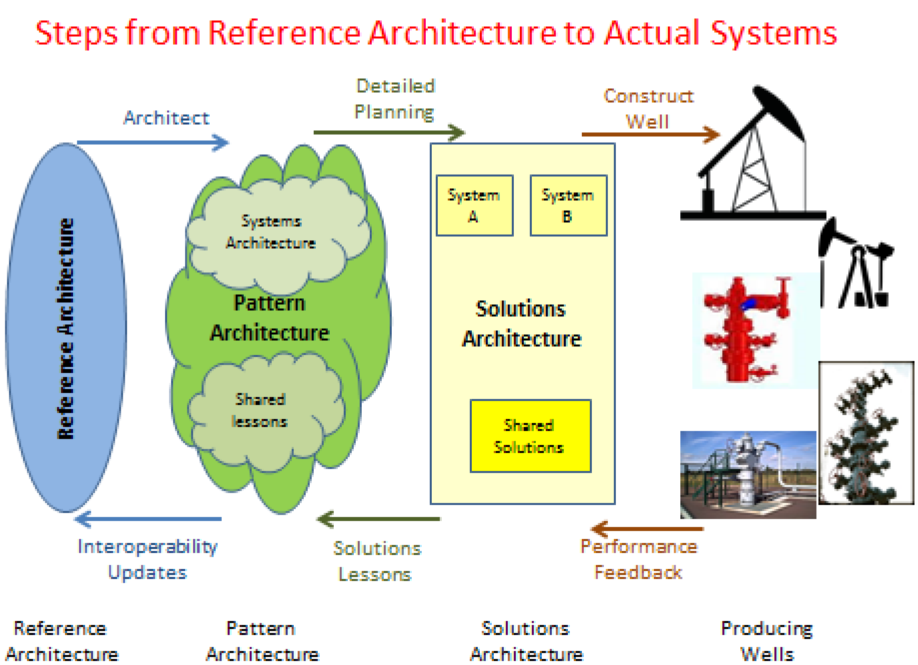


Figure 5- Reference Architecture Life Cycle Overview with Pattern / Solutions Architectures and the Product of Constructed Wells

A Reference Architecture provides a proven template solution for drilling systems automation architecture. It also provides a common vocabulary with which to discuss implementations, often to stress commonality. The primary purpose of a Reference Architecture is to guide and constrain the installations of Pattern Architectures and thence Solution Architectures. Adopting a Reference Architecture within an industry offers the opportunity to accelerate delivery through the re-use of an effective solution and provides a basis for governance to ensure the consistency and applicability of technology use within the industry.

Adopting a Reference Architecture within an industry can accelerate delivery of an effective solution through the adoption of its commonality aspects and can provide a basis for governance to ensure the consistency and applicability of technology use within the industry. In the field of software architecture, many empirical studies have shown the following common benefits and drawbacks from adopting software reference architecture within organizations:

- Improvement of the interoperability of the software systems by establishing a standard solution and common mechanisms for information exchange
- Reduction of the software project development costs through the reuse of common assets
- Improvement of internal organization communications because stakeholders share the same architectural mindset
- Influencing the learning curve of developers who need to learn the software's features.

These same attributes apply to a DSA Reference Architecture adopted by the industry.

Wikipedia definition offers further value insights. "A reference architecture in the field of software architecture or enterprise architecture provides a template solution for architecture for a particular domain. It also provides a common vocabulary with which to discuss implementations, often with the aim to stress commonality. Software reference architecture is a software architecture where the structures and respective elements and relations provide templates for concrete architectures in a particular domain or in a family of software systems."

The Reference Architecture described in this DSA Roadmap report is the culmination of many discussions with experts inside and outside the oil and gas industry and is built on the DoDAF methodology to create a foundation for DSA development in drilling operations globally. As the industry designs Solution Architectures, the experiences gained can be fed back into the Reference Architecture to maintain it as a current industry best practice. This will require the industry Reference Architecture be maintained and updated by an industry standards organization.

Distinctions in Hierarchy Levels of Systems Architecture

Achieving interoperability between many different and evolving systems is critical for success of industry-wide DSA. Interoperability drives the usability, performance and dependability of user level applications. The hierarchy of systems architecture enables the benefits of interoperability to be defined through a common approach at the reference level while enabling innovation and competition at the solutions level.

Reference Architecture

The reference architecture is a high-level system view for drilling and completion that provides a common environment to enable interoperability. A hierarchy below this level includes:

- Pattern architecture ranging from multiple similar land wells in a single location to single exploration deepwater wells
- Solutions architecture developed for a specific project under the umbrella of both the Reference Architecture and the Pattern Architecture.

Pattern Architecture

Pattern architecture is the next level development of the systems architecture hierarchy and provides various defined patterns of drilling operations having key distinctions. The bookends of these patterns highlighted in this report are:

- Land drilling multiple development wells
- Deep offshore exploration wells.

Other patterns exist that form architectures across this full spectrum of well and operation types. Because they employ the same systems to differing degrees, Patterns are not expected to differentiate between vertical, high angle and horizontal wells.

The full range of wells envisaged as specific patterns are described below in Capability Viewpoint.

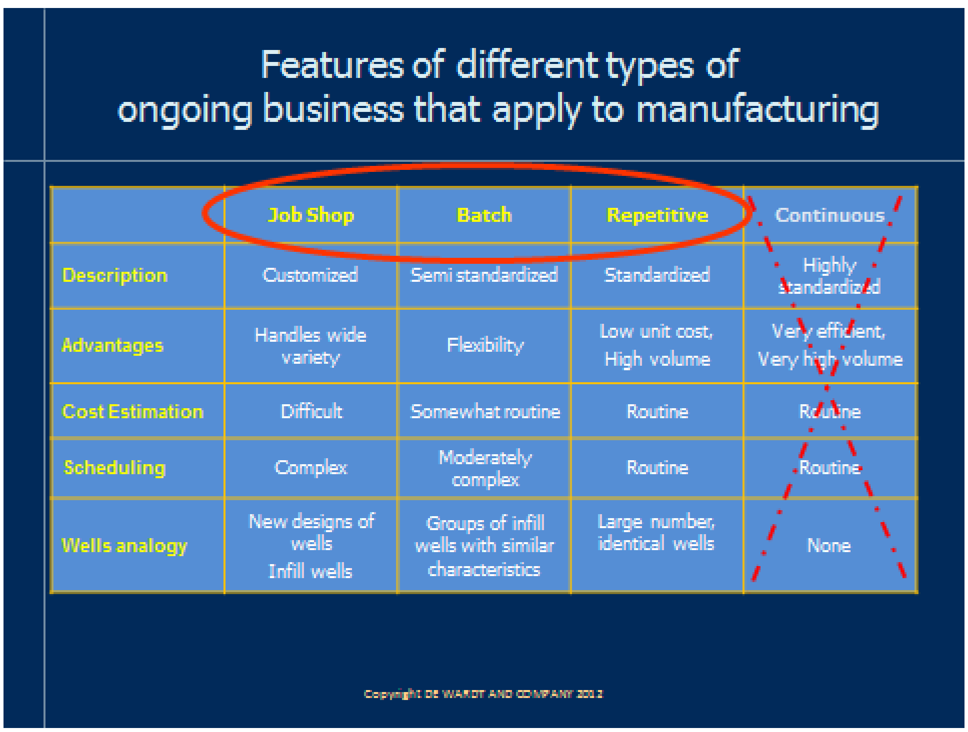
The steps across the pattern architecture are driven by the business models that apply to various drilling operations. Business models describe four types of ongoing businesses and projects. The continuous process model does not apply to drilling operations because this is a chemical process plant model. The remaining three variants of ongoing business apply across a range of drilling operations (Figure 6).

The definition of business type was introduced to the industry in February 2010.[5] This is a critical well operation distinction that drives selection of planning methods and operational management. Four key types of business process apply to well construction, or the drilling and completion of wells. At one extreme are projects, which are typically exploration and appraisal wells. These are one off type operations that require the ability to manage uncertainty. At the other extreme are repetitive operations that result from large numbers of identical wells. Repetitive wells possess characteristics that provide the maximum opportunity to apply manufacturing methods to well construction.

The key business types and their attributes for wells follow the key manufacturing types (see Figure 6):

- Projects—one off complex and uncertain wells
- Customized—difficult wells that require management of uncertainties
- Batch—semi standardized, somewhat routine wells
- Repetitive—standardized routine wells that are drilled and completed in high volumes.

Continuous—applies to process plant and are not relevant to drilling and completion operations.



Features of different types of ongoing business that apply to manufacturing

	Job Shop	Batch	Repetitive	Continuous
Description	Customized	Semi standardized	Standardized	Highly standardized
Advantages	Handles wide variety	Flexibility	Low unit cost, High volume	Very efficient, Very high volume
Cost Estimation	Difficult	Somewhat routine	Routine	Routine
Scheduling	Complex	Moderately complex	Routine	Routine
Wells analogy	New designs of wells Infill wells	Groups of infill wells with similar characteristics	Large number, identical wells	None

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Figure 6- Ongoing Business Types in Drilling and Completion

The uniqueness of some drilling operations adds projects into the scale, which completes the range.

The table (Figure 7) below provides a range of characteristics of these various operations and defines the distinctions across the range of Pattern Architecture. These characteristics deliver the various options that the Pattern Architecture will represent and the options through which lessons learned in Solutions Architectures drive updates to the Reference Architecture.

Features of different types of business process that apply to well construction

	Projects	Job Shop	Batch	Repetitive
Description	One off	Customized	Semi standardized	Standardized
Advantages	Maximize unique value	Handles wide variety	Flexibility	Low unit cost, High volume
Cost Estimation	Complex	Difficult	Somewhat routine	Routine
Scheduling	Complex, changes	Complex	Moderately complex	Routine
Wells analogy	Expl / Apr wells Radical Redesign	New designs of wells Infill wells	Groups of infill wells with similar characteristics	Large number, identical wells

Figure 7- Business Types Applied to Drilling and Completion Operations

This Pattern Architecture is where the type of drilling operation is defined under a common solution to enable development of interoperable systems and components.

It is readily apparent that most oilfield drilling operations begin as a project. These operations transition to ongoing business as activity shifts to multiple wells in a field. The ongoing business stage goes through a life cycle that begins with the job shop and transitions to batch processing as the wells becomes better defined and more standardized. Furthermore, the applicable type of process may revert to job shop from a batch process if a nonstandard well is injected into the sequence for any reason, such as changed subsurface geology or new well design.

It is important to adjust the planning and execution activities to match the type of process that is relevant to the operation. In the extreme, applying a project type process to repetitive operations is a waste of time, effort and money in the planning phase. Conversely, applying repetitive planning and execution activities to a project type operation will result in a major execution failure.

The goal of many drilling and completion operations is to reduce cost and to deliver predictable results that meet the planned cost, schedule and functionality. To do this, these operations must transition toward repetitive and continuous type operations. This requires a change from flexibility to standardization, which is only possible when consistent geology and reservoir conditions enable development wells to become repeatable. The goal of this exercise, then, is to develop highly standardized “manufactured wells.”

There are two operations caveats: repetitive wells can revert to Customized (job shop) or project type business processes when major design or technology application changes are introduced; and the ability to access the full benefits of applying manufacturing techniques requires a drive toward standardization leading to more repetitive style wells and operations.

The well delivery process must be designed for a specific type of operation or to be scalable so that it is intentionally adjusted to match a variety of types of operation.

	Projects	***Ongoing Business***			
Attributes	**Projects**	**Customized (Job Shop)**	**Batch**	**Repetitive**	**Continuous**
Description	One off	Customized	Semi standardized	Standardized	Highly standardized
Advantages	Maximize value of unique opportunity	Able to handle wide variety	Flexibility	Low unit cost, high volume efficiency	Very efficient, very high volume
Cost estimation	Complex	Difficult	Somewhat routine	Routine	Routine
Scheduling	Complex, subject to change	Complex	Moderately complex	Routine	Routine
Wells analogy	Exploration and Appraisal wells.	Infill wells requiring unique solutions.	Groups of infill wells with similar characteristics	Large number of identical wells with some defined	None

	Projects	*Ongoing Business*			
Attributes	**Projects**	**Customized (Job Shop)**	**Batch**	**Repetitive**	**Continuous**
	Radically redesigned wells or a radical change indrilling / completion technology	New designs of wells in a well know region		options (Manufactured Wells)	
Uncertainty	High – core aspect of this type of process, requires significant and continuous human intervention	Medium to high – a balance between the algorithm application and the human control	Low to medium – addressed with algorithms with human monitoring / intervention	Low – can be primarily addressed with algorithms	None
Repetition in wellbore aspects	None	Low	Medium	Very high	Absolute
Repetition in surface operations	Medium	High	Very high	Very high	Absolute
Human intervention	Very high	High	Medium	Low	None
Automation application	Specialized – surface repetitive operations, downhole operations with sophisticated sensors / algorithms / control / actuation, significant human monitoring and intervention	Specialized – surface repetitive operations, downhole operations with some routine and some specialized control assigned by humans	High levels of automation selected and directed by humans	Very high levels of automation applied to both surface and downhole operation supervised by humans (onsite or remote)	Autonomous

	Projects	*Ongoing Business*			
Attributes	**Projects**	**Customized (Job Shop)**	**Batch**	**Repetitive**	**Continuous**
Pattern Architecture (2016)	Single exploratory land wells Single exploratory offshore wells Single exploratory deepwater offshore wells	Single land appraisal wells Single offshore appraisal wells	Single or a few land development wells in well-known area Single or a few offshore development wells in well-known area	Multiple repeatable land development wells Multiple repeatable offshore platform development wells	None

Table 1 - Features of the Different types of Operations and their Impact on DSA

Table 1 forms the basis for determining the distinct well and operations types in the Pattern Architecture. Nine distinct patterns can be correlated under four business operations types, which form a hierarchy of Pattern Architecture for automating drilling and completion operations.

The primary levels of distinction and the subsidiary levels in pattern architecture applicable to drilling systems automation are:

1. Project style wells / drilling completion operations
    a. Single exploratory deepwater offshore wells
    b. Single exploratory offshore wells
    c. Single exploratory land wells
2. Customized (job shop) wells / drilling completion operations
    a. Single offshore appraisal wells
    b. Single land appraisal wells
3. Batch wells / drilling completion operations
    a. Single offshore development wells in well-known area
    b. Single land development wells in well-known area
4. Repetitive wells / drilling completion operations
    a. Multiple repeatable offshore platform development wells
    b. Multiple repeatable land development wells

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The DSA Roadmap focuses on the Reference Architecture and drops into the higher levels 1 through 4 of Pattern Architecture.

The distinctions between the levels 1 through 4 above are for the expansion toward Solutions Architecture, which crosses from cooperation on standards to competing on innovation; this defines the envelope of the DSA Roadmap project.

Pattern 1 – Project Operations

These types of wells are analogous to space flight operations in which the actual operating environment is revealed from data measurements at regular intervals after the plan has been confirmed or modified. The low frequency and high latency from space flight data transmissions are similar to those experienced with mud pulse and EM telemetry from downhole, which requires staged updates to any autonomous system. Hard wire pipe reduces the constraints of the telemetry system (dependent on the system employed), enabling a different approach to automation adoption though continuous monitoring, analysis and surface-initiated control updates.

Repetitive surface tasks that are readily mechanized, especially those that can remove humans from risk to their safety, will be automated. Downhole tasks pose a much higher challenge for the application of automation because the environment is uncertain. This uncertainty will require humans-in-the-loop for many years, which will lead to a de-facto latency effect. These operations will require significant human monitoring and intervention.

Pattern 2 - Customized (Job Shop) Operations

These wells have individual characteristics and include some elements that are common in other operations across the field or region. They have similarities to Pattern 1 in terms of uncertainties offset by some repetition from similar operations. Humans will be required to intervene in many of the automation loops to offset levels of uncertainty.

Pattern 3 – Batch Operations

Batch operations apply to wells that are similar, or to previous wells drilled in the area but that are not exact matches as in Pattern 4—Repetitive Operations. These wells do, however, have sufficient similarities to allow selection of levels of automation in drilling the wells that are closer to those for Pattern 4 than for Pattern 2 or 1. Repetitive surface tasks that are readily mechanized will be automated with humans in oversight only, especially those that can remove humans from risk to their safety.

Pattern 4 – Repetitive Operations

Repetitive wells offer the closet pattern analogy to manufacturing and to the application of automation to manufacturing. Repetitive surface tasks that are readily mechanized will be automated without any human in the loop. Downhole tasks in this repetitive environment can have significant levels of automation and will primarily require human supervisory control only when the operations deviate from plan. These operations will employ high levels of automation with human supervisory control.

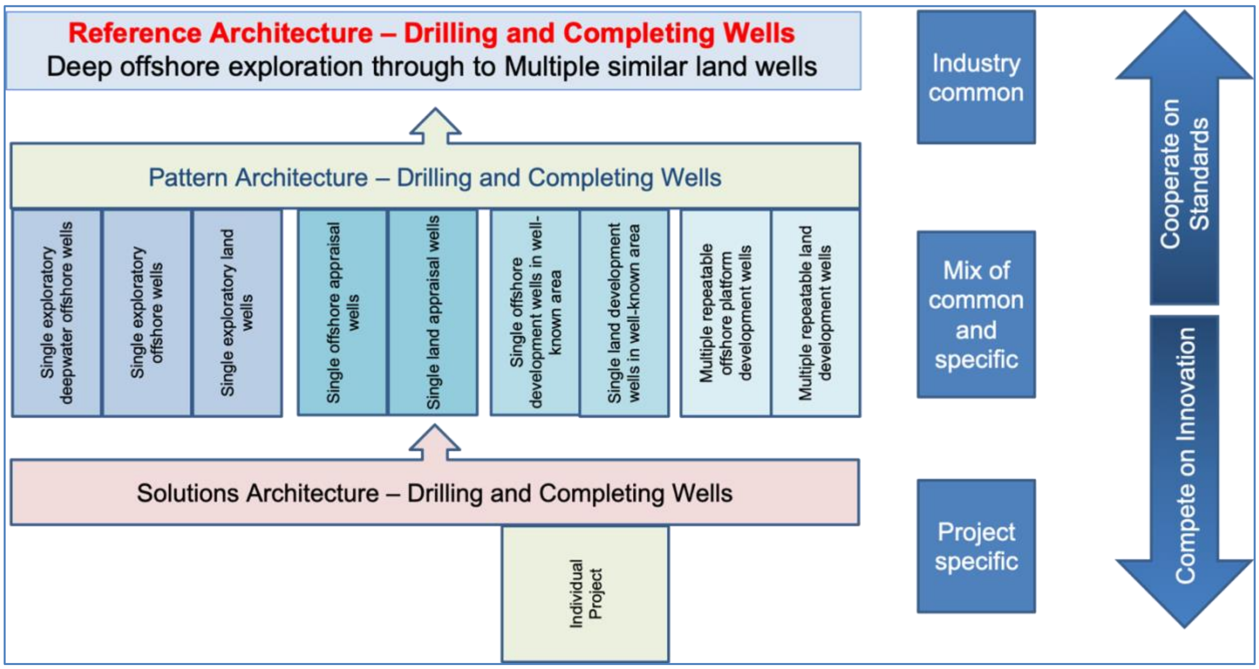

Figure 8 - Hierarchy of Systems Architectures

Solutions Architecture

Solutions architecture is a specific, detailed solution developed for a project that falls under the guidance from the Reference and Pattern Architectures. The solutions architecture is used to solve specific project issues, and when a team opportunity is enabled to differentiate one drilling operation from another.

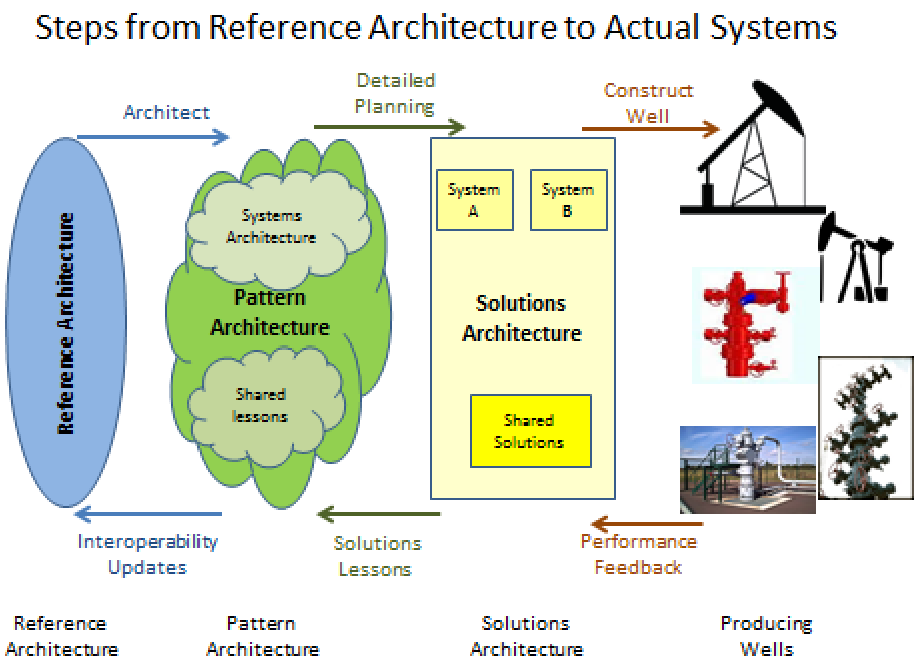

Figure 9 - Reference Architecture Life Cycle Overview

All Viewpoint (AV) from DoDAF

This is the overarching aspects of architecture context that relate to the Reference Architecture, the Pattern Architecture and the Solutions Architecture.

AV-1 Overview and Summary Information

Describes a Project's Visions, Goals, Objectives, Plans, Activities, Events, Conditions, Measures, Effects (Outcomes), and produced objects.

Identification

Drilling Systems Reference Architecture is the means by which the industry can take a consistent view to interrelationships between various hardware and software elements. It provides a consistent basis on which to develop interdependent systems and subsystems. It is the level of abstraction at which standards and other cooperative tools will be developed for common benefit.

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Purpose

This Reference Architecture is needed to create a common view of the relationship of systems and subsystems across the industry that collectively deliver a drilled and completed well. The Reference Architecture forms a foundation for interoperability amongst disparate entities and organizes processes toward a common goal of safe, high performing and functional operations (drilling and completion) and effective products (wells). Interoperability is required for effective automation and enables performance improvement.

Scope:

Systems architecture is a new concept to apply to whole drilling systems. The scope of the architecture matches the scope of the DSA-R previously described. This roadmap is limited to defining the Reference Architecture and simply highlighting the Pattern and Solutions Architecture relationships. The time frame is 2016 to 2025.

Context:

The constituents of drilling and completion operations is highly fragmented and have evolved from operator departments to contracted businesses on incentive schemes to multiple players on day rate. This evolution, and the contracts used to combine the players, lacks an architectural approach to systems delivery. Industrial automation from the 1990s has clearly shown that success of application requires interoperability. Interoperability can only be achieved if architecture that enables disparate players to operate in functional control loops and communicate between loops is developed and applied. Drilling and completion operations have clear distinctions at a detailed level and commonality at a general level. The Reference Architecture is intended to address the commonality and thus enable companies to develop components, subsystems or systems that will be consistently interoperable. Drilling Systems Reference Architecture is an industry requirement; it is an umbrella over Well and Operation Pattern Architecture that addresses families of operation types so they may share their commonality and, thereafter, over well Project Solutions Architecture that addresses the details of a specific project.

Status:

The Reference Architecture has been developed based on expertise and experience from the industry. It is intended that that this architecture be challenged, reviewed and updated by the Drilling Systems Automation Roadmap Initiative Joint Industry Project organizations and issued at an appropriate interval to the industry. The concept is that this Reference Architecture be updated through industry input and managed and maintained in a manner that benefits the industry.

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The DSA Reference Architecture was exposed for challenge at the January 2018 IADC managed workshop. The workshop participants endorsed the Systems of Systems and Systems of Interest development described in this report.

AV-2 Integrated Dictionary

An architectural data repository with definitions of all terms used throughout the architectural data and presentations

Systems: a set of things working together as parts of a mechanism or an interconnecting network.

Automatic: a device or process working by itself with little or no direct human control.

Automation: the use of automatic equipment in an operation or process.

Performance: an action, task, or operation seen in terms of how successfully it was undertaken.

Quality: the standard of something as measured against similar things; the degree of excellence of something.

Drilling Systems Automation: devices and processes that combine to drill a wellbore with limited human input.

Acronyms used in this report:

DSA-R: Drilling Systems Automation Roadmap

DSABOK: Drilling Systems Automation Body of Knowledge

DSAD&CF: Drilling Systems Automation Decision and Control Framework

DCF: Decision and Control Framework (short form for DSAD&CF)

MES: Manufacturing Execution System

MRP: Manufacturing Resource Planning

SoI: Systems of Interest

SoS: Systems of Systems

UC: Use Case

WC: Well Construction

WCES: Well Construction Execution System

Systems Viewpoint (SV)

International Council on Systems Engineering (INCOSE) provides some clear guidance on systems architecture:
"Systems-of-Systems (SoS) are defined as an interoperating collection of component systems that produce results unachievable by the individual systems alone. The systems considered in ISO/IEC 15288 are manmade and created and utilized to provide services in defined environments for the benefit of users and other stakeholders. These systems may be configured with one or more of the following: hardware, software, humans, processes (e.g., review process), procedures (e.g., operator instructions), facilities, and naturally occurring entities (e.g., water, organisms, minerals). In practice, systems are considered products or services. The perception and definition of a specific system, its architecture and its system elements, depend on an observer's interests and responsibilities. One person's system of-interest can be viewed as a system element in another person's system of-interest. Conversely, the system may be viewed as being part of the environment of operation for another person's system-of-interest." [5]

This concept is illustrated in the figure below.

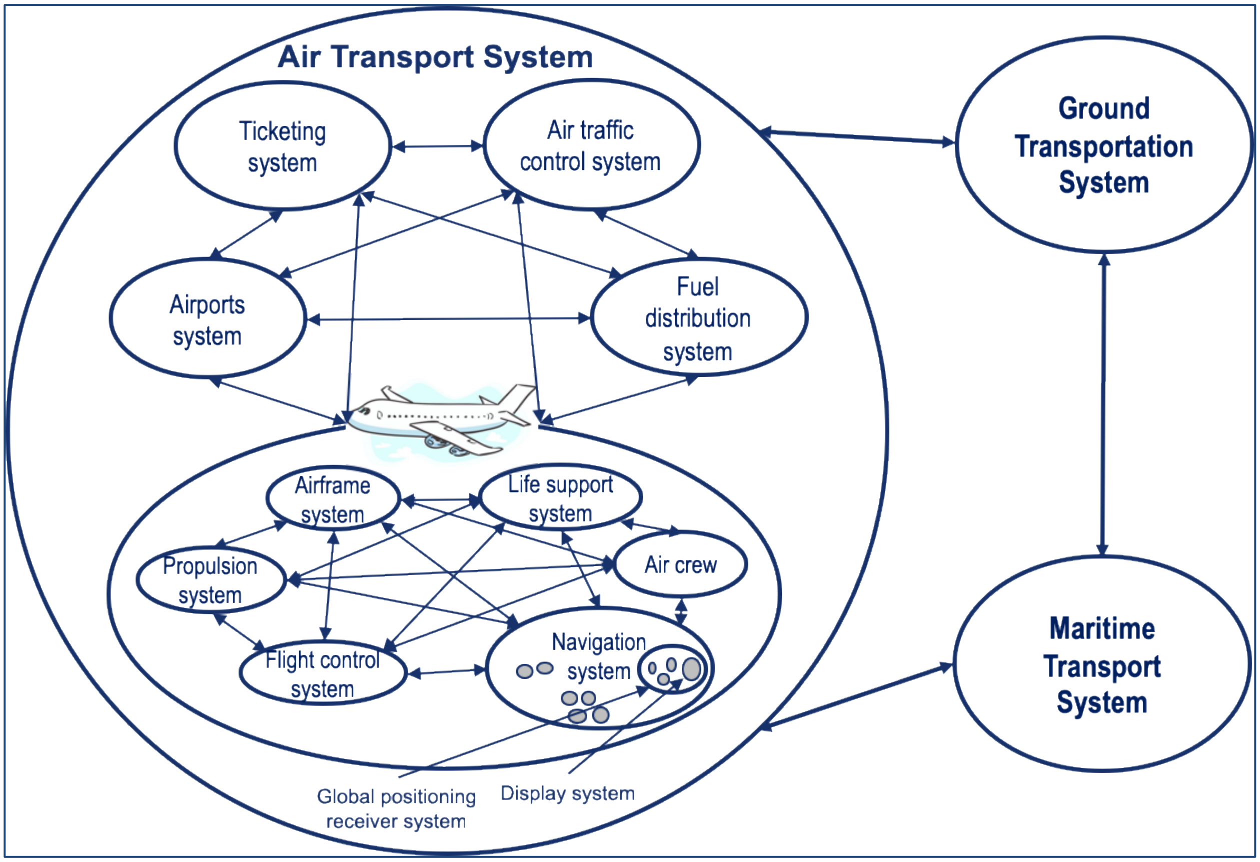

Figure 10 - Example of Systems of Interest in an Aircraft and its Environment of Operation within a Transport System of Systems

The following descriptions are taken from INCOSE as clear representations of expert descriptions for SoS.

"The Global Positioning System (GPS)," which is an integral part of the navigation system on board an aircraft, is a unique system rivaling the complexity of the air transportation system. Another characteristic of SoS is that the component systems may be part of other unrelated systems. For instance, the GPS may be an integral part of automobile navigation systems.[6]

The following challenges all influence the development of Systems of Systems:

1. *System elements operate independently*. Each system in a System of Systems is likely to be operational on its own.
2. *System elements have different life cycles*. SoS involves more than one system element. Some system elements may be in their development life cycle while others are already deployed as operational. In extreme cases, older systems elements in SoS might be scheduled for disposal before newer system elements are deployed.

3. *The initial requirements are likely to be ambiguous*. The requirements for a System of Systems can be very explicit for deployed system elements. But for system elements that are still in the design stage, the requirements are usually no more explicit than the system element requirements. Requirements for SoS mature as the system elements mature.
4. *Complexity is a major issue*. As system elements are added, the complexity of system interaction grows in a non-linear fashion. Furthermore, conflicting or missing interface standards can make it hard to define data exchanges across system element interfaces.
5. *Management can overshadow engineering*. Since each system element has its own product or project office, the coordination of requirements, budget constraints, schedules, interfaces and technology upgrades further complicate the development of SoS.
6. *Fuzzy boundaries cause confusion*. Unless someone defines and controls the scope of a SoS and manages the boundaries of system elements, the definition of the external interfaces is not controlled.
7. *SoS engineering is never finished*. Even after all system elements of a SoS are deployed, product and project management must continue to account for changes in the various system element life cycles, such as new technologies that impact one or more system elements, and normal system replacement due to preplanned product improvement."

A conceptual overview of a Well Construction System within a field development System based on the INCOSE example and description is presented in Figure 11. This overview provides a guide for further development of a full systems interface description for Drilling Systems Automation delivering Well Construction.

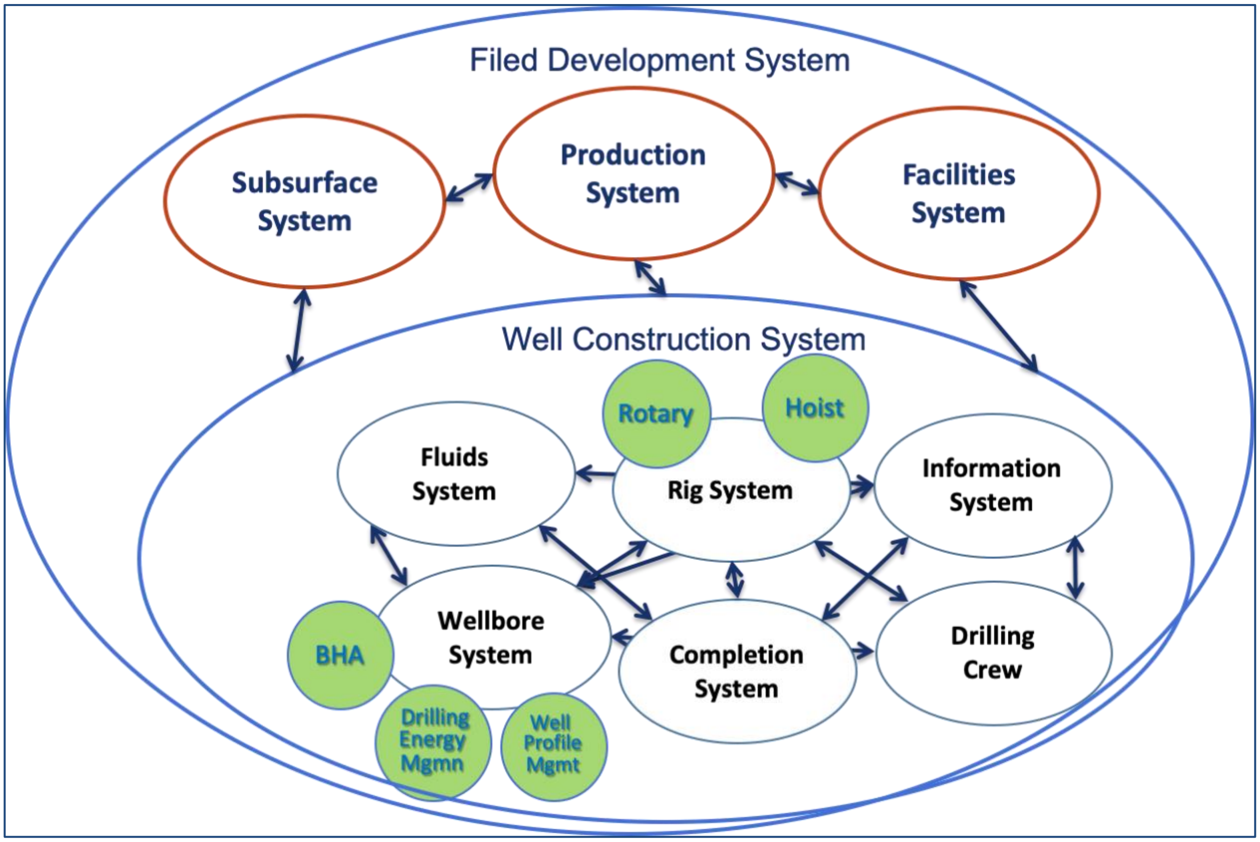

Figure 11: Well Construction System within Field Development System – an overview

SV-1 Systems Interface Description

Drilling systems automation involves the control of highly complex interrelated systems that often operate in a highly uncertain environment. Drilling systems architecture is composed of multiple interconnect systems that operate through complex relationships to deliver a well.

These interrelated systems have not previously been defined in a systems of systems approach. The traditional contracting is siloed and piecemeal, which limits its impact in defining a framework for systems of systems. In some instances, technology combination has resulted in a subsystem, such as BHAs, that are not common across the full spectrum of the business. The diagram below forms a map of the primary systems that operate across the full range of the reference architecture.

5 of 14: Systems Architecture

The Systems of Systems (large blue circles) are identified as the primary systems that deliver a well. Figure 12 depicts delivery of wells by DSA through each well's life cycle of construction, intervention and abandonment.

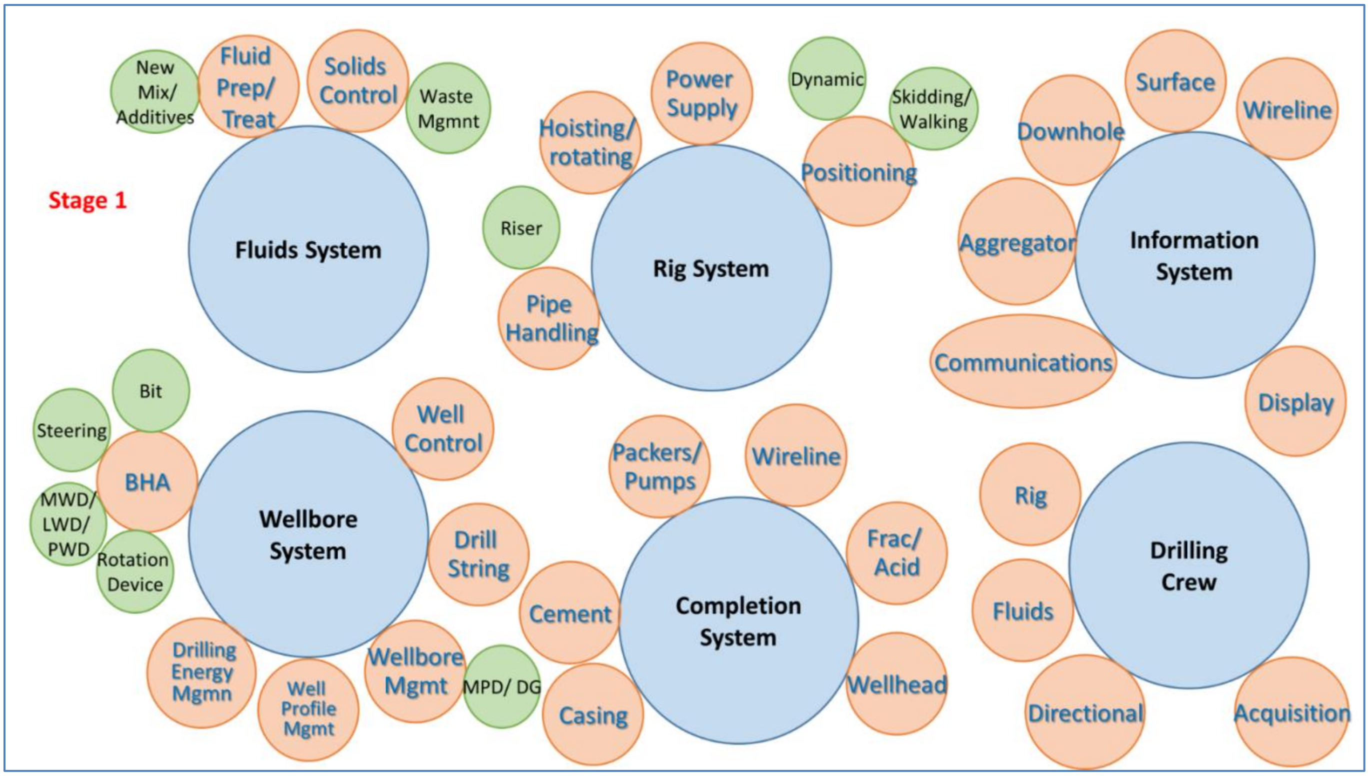

Figure 12 - Drilling and Completion Systems of Systems / Systems of Interest

Within the 'Systems of Systems' are 'Systems of Interest.' These are depicted by the orange discs. Systems of Interest are those whose life cycle is under consideration. These systems of interest are recommended as the focus of automation improvements through the cognitive cycle of data acquisition, analysis, decision and action. Systems of interest provide a nucleus within which automation application can enhance performance. Ultimately, DSA will only be achieved when the critical systems of interest have each achieved a status of automation that maximizes the benefits of control systems and supports the humans to the maximum extent.

The Information System and Drilling Crew Systems are expected to merge into a SCADA system that includes all wellsite data, control systems and supervisory wellsite personnel. This emergence is described in the Information and Data View later in this chapter.

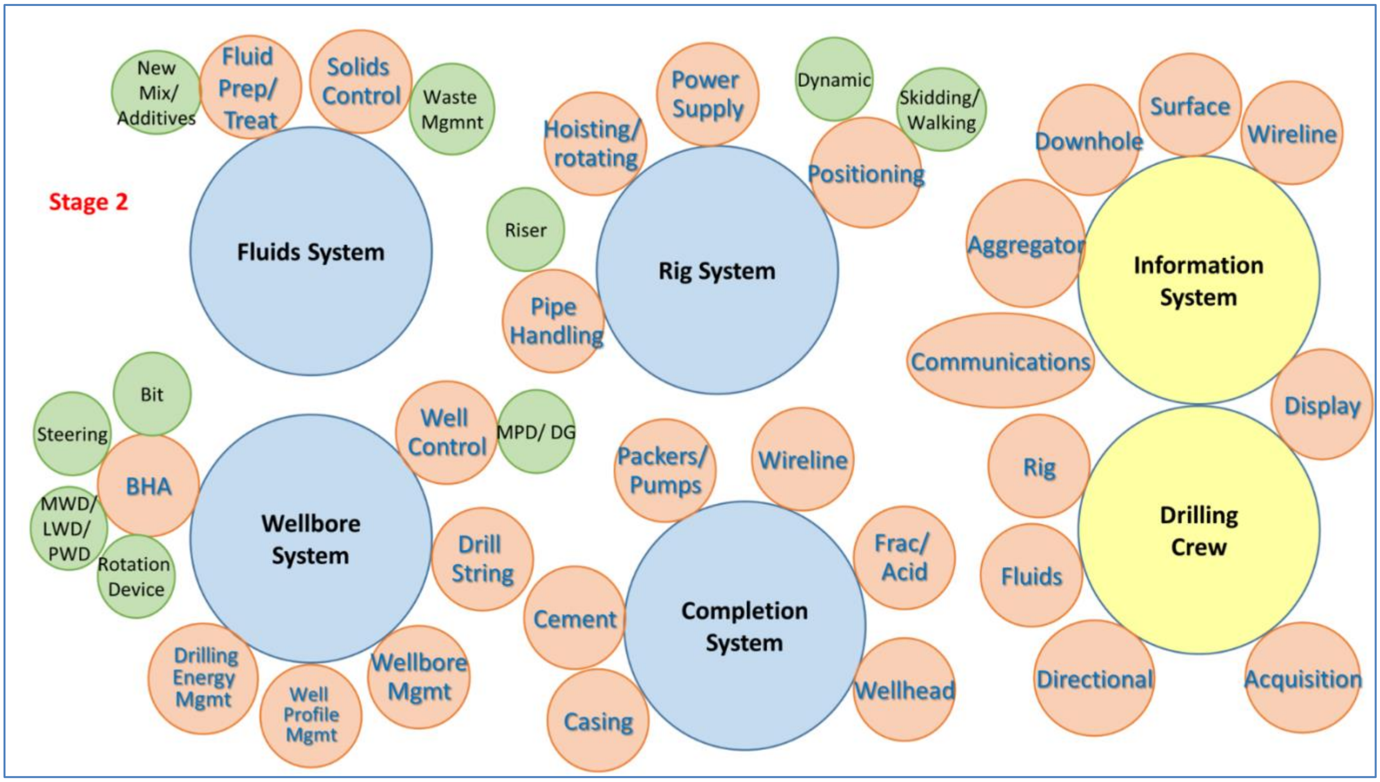

Figure 13 - Emergence of SCADA System

SV - 2 Systems-Systems Matrix – Systems of Interest

The relationships among systems in a given Architectural Description can be designed to show relationships of interest, such as system-type interfaces or planned vs. existing interfaces.

Relationships are multiple, complex and highly interdependent. The Systems of Interest (SoI) approach provides the means to identify the key systems delivering value and to form a focus to describe their interrelationships with other systems.

The intention of the DSA Roadmap is to describe the future development to a full system automation state in DSA. The chosen method is to focus on the development of various aspects in Systems of Interest with the intention that these combine to deliver a full system automation. Systems of Interest provide a focused view of subsystems that can be automated with the necessary development of sensors, communications, controls, etc. They also provide a focus to define the value delivered.

A broader approach could be less successful because sensor development spread across all systems may not be effectively combined to close a loop necessary for delivering improved performance. However, Systems of Interest (SoI's) must be robustly developed with the Systems Architecture otherwise they could expose the whole SoS to a failure mode. The primary Systems of Interest for developing the reference architecture are listed below.

Systems of Interest for Drilling Systems Automation

Wellbore System
- Bottom hole assembly
- Drill string
- Well control system / MPD system
- Well Profile Management
- Well Bore Management
- Drilling Energy Management

Fluids System
- Fluids preparation, treatment and pumping
- Solids control, waste management

Rig System
- Hoisting and rotating
- Pipe handling system
- Power supply
- Positioning

Drilling Crew
- Rig Crew
- Directional Crew
- Fluids Crew
- Data Acquisition Crew

Information System
- Downhole data acquisition

- Surface data acquisition surface
- Wireline Logging
- Communications
- Aggregator / Historian
- Human Machine Interface – Display

Completion System

- Cementing System
- Casing
- Wellhead
- Well Flow Control - Packers/ Downhole Pumps
- Well Intervention – Slickline / Coiled Tubing
- Reservoir Stimulation - Fracturing / Acidizing
-

Systems of Interest – Process Management

The wellbore system of interest includes three process management systems of interest which are expanded below.

- Well Profile Management
  - Trajectory
  - Well placement
  - Tortuosity – major and micro

- Well bore Management
  - MPD, which could move to Well Control as the industry adopts it as automated well control
  - Pore pressure
  - Hole cleaning
  - Stability
  - Quality

- Drilling Energy Management
  - Drilling Dynamics
  - ROP Maximization
  - Hydraulics

Systems of Interest Hierarchy – Epics, User Stories, Use Cases, States and States Transitions

Systems Architecture includes Use Cases and States; both important tools for enabling interoperable automated systems.

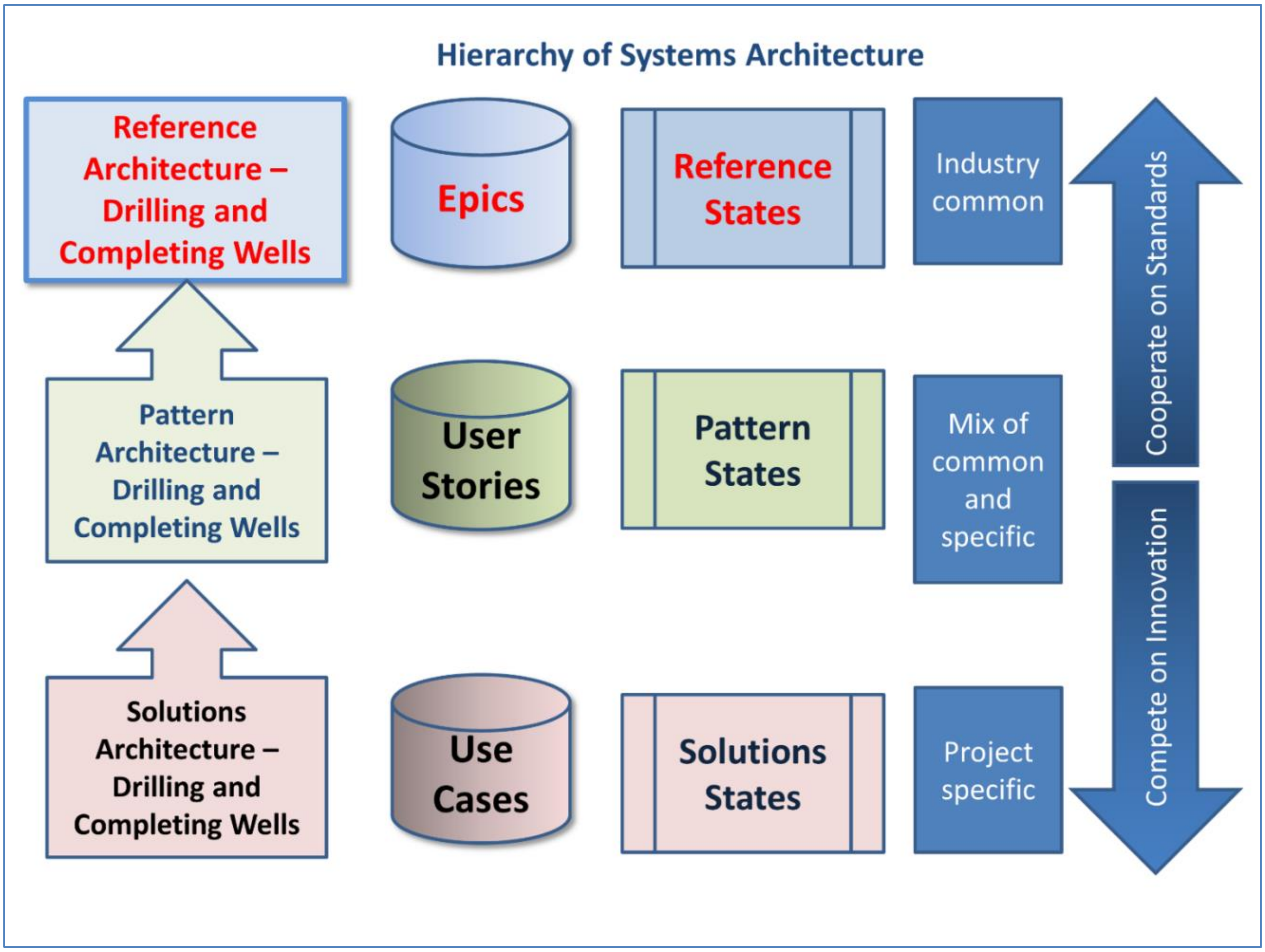

Figure 14 - Hierarchy of Use cases and States

Epics, User Stories and Use Cases

Further description of systems architecture requires systems engineering development processes to fully develop the process flow at the solutions level. The relationship with the Reference Architecture can be manifested by a hierarchical breakdown of needs, actions and outcomes. Epics, User Stories and Use Cases can develop the information necessary to complete the systems architecture.

The application of automation within systems architecture requires the definition of use cases; these are “a series of interactions between an outside entity and the system, which end by providing business value.”[7] A set of agreed use cases provides a common intent for all involved parties, systems and activities in a drilling and completion operation. Use cases are best developed and understood by drilling down to them through a hierarchy of epics, then user stories and then use cases. This combination of epics, user stories and use cases provides the framework to identify systematic needs from the automation system. This, in turn, maps across all sub elements of the automation system to identify critical capabilities and technologies required to achieve the desired levels of systemic drilling systems automation.

An effective way to develop use cases and understand the relationships between them in terms of the systems is to use the AGILE development method of formulating epics and user stories, and then to affinitize them into themes.

The advantage of this method is to order the user stories into a logical hierarchy based upon the Reference, Pattern and Solutions Architectures. For DSA, the epics would represent the “intent” of the user of the drilling system at the Reference Architecture level, the Patterns (various types of drilling operations) would drive the user stories, and the actual Solutions Architecture would drive the Use Cases.

A user story is simply something a user wants. Examples are: “As a Driller I want to make a rapid, safe connection so that I can trip pipe as quickly as possible” or, “As a Derick Hand I want to rack pipe in order in the fingers so that pipe handling is safe and efficient.” The standard format for a user story is: “As a persona I want/can/am able to/need to/ do ‘x’ so that some reason is satisfied.”

An epic is a large user story that requires other smaller user stories. An example of an epic would be “Drill-a-stand,” “Trip-out-of-hole” or “Run casing.” Each of the epics requires user stories to take place as sub elements of the activity.

A use case is a list of steps, typically defining interactions between a role (known in Unified Modeling Language (UML) as an "actor") and a system to achieve a goal. The actor can be a human, an external system, or time.[7] Examples of use cases include Ramping-up-Pumps, Tagging-Bottom and Optimizing ROP. Use cases have been developed and standard templates generated by the Drill-a-Stand team under SPE DSATS. These templates are very useful reference materials for applications. However, the actual activity steps, their sequencing, their durations and their intent will be specific to a solution and not generic to the Reference

Architecture. Similarly, User Stories are specific to unique well type operation at the Pattern Architecture level.

Use Cases and States Relationship

States define the activity that is in process at any given time. In manual operations, states are initially defined by a manual report; these are being superseded by state engine identifications based on the combined output of multiple sensors.[8,9] Use cases tend to pair with the various states. There can be a set of states defining the beginning and end of a use case, as well as internal transitions within a use case. Transitional states could lead to alternate use cases.

Knowing the use cases the automation system is addressing and the states associated with the implementation of the use case is very valuable to successful adoption of automation.
An automation state example explains this interrelationship: “The bit is on-bottom drilling.” This state (action) is realizing the User Story “Drill a Stand.” While this action is active, the automation system engages a drilling control system designed to optimize rate-of-penetration. This enables the use case “Optimize ROP.”

Another automated system, running concurrently at a monitoring level, may be a use case “Monitor for off nominal conditions.” The automation state of the system may be “Automated Drilling-Normal,” while the well state is “Controlled.” This use case would terminate once it is time to add more pipe to the drillstring. However, in this example, the detection of a possible influx invokes an alternate use case. Because the potential outcome of this condition could cause the well state to degrade from “Controlled” to “Uncontrolled,” prescribed actions must mitigate this risk. Therefore, the automation state changes from “Automated Drilling-Nominal” to “Automated Drilling-Handle Influx” and the “Drill a Stand” epic transitions to another epic such as “Control the well.” The “Automated Drilling-Handle Influx” state could transition to “Shut in Well” if the conditions were dire. Yet another outcome could be to turn the automation state to “Deactivated,” return all operations to a “safe state” and permit the driller to take over.

Suspension of Operations

Suspension of events is possible in drilling operations, which provides a significant advantage over aviation and aerospace. Essentially, there is low probability that flight can be paused if an event occurs on an aircraft in flight. In drilling, many incidents can be paused by activating a safe mode for the drilling operation; essentially the rig will not “fall out of the sky” unless it is an out of control well event. The ability to pause drilling operations in a defined mode provides drilling systems automation with a means to put the operation on hold and await updated instructions or human operator intervention when something untoward occurs. The 'safe mode' provides the driller with the contextual information of the operating systems, not necessarily the well state.

State Traceability

Traceability of state and information: An often-forgotten context that is required for an automation system to perform reliably and safely relates to the veracity of the information. Consider Priyadarshy's model of the various elements of data.[10] One of the key elements is veracity. This element considers the reliability and truthfulness of the data. More explicitly, data, especially contextual state data, needs to be traceable and reliable enough for automation.

All parties involved in the creation and use of contextual or state data must agree on the derivation of the state and what it implies. Failure to do so may lead to catastrophic misalignment across multiple vendors interoperating on the controls of the drilling operation.

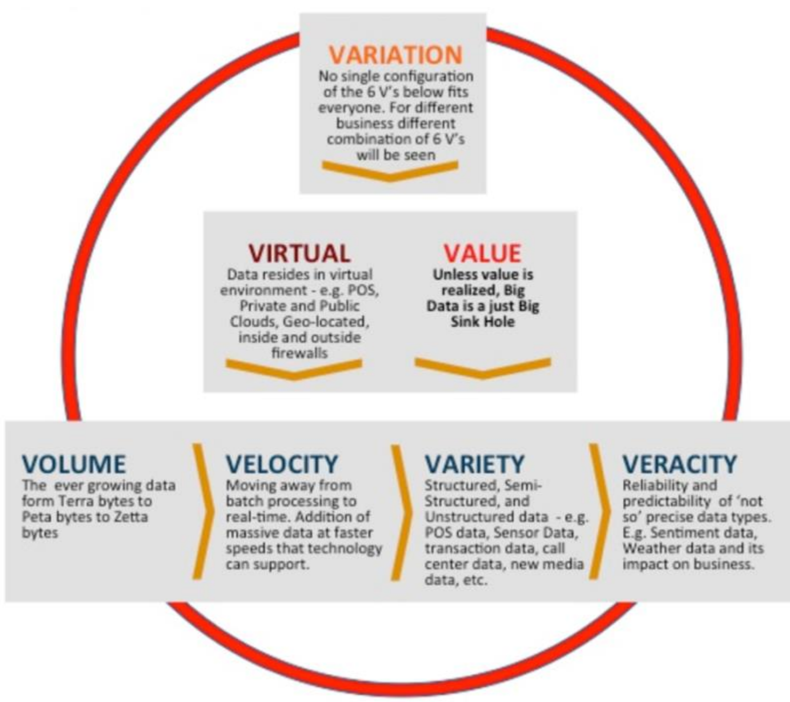

Figure 17 - The Seven 'V' of Big Data[9] (Copyright Dr. Satyam Priadarshy - used with permission)

The mapping to User Stories with Systems of Interest at multiple levels provides a tool enabling definition of the connectivity between various SiS during the processes of drilling and completing a well. Figure 18 is not a definitive map, but an example of methodology.

Application for this tool across the full spectrum of the SoS and SiS Tier 1 and Tier 2 provides a powerful mechanism to establish and connect all relationships on a complex automated system.

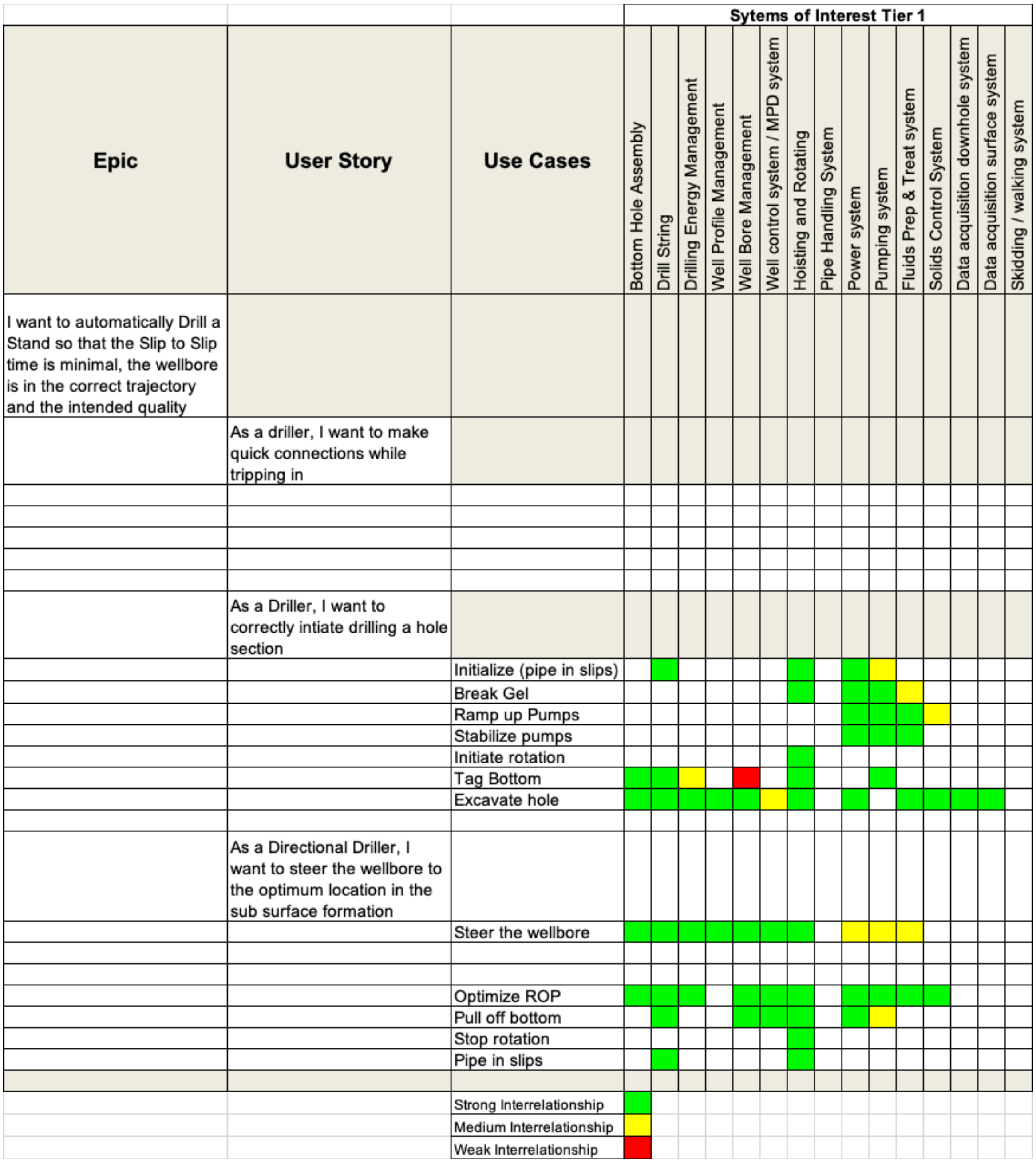

Figure 18 – Mock-up Demonstration of Mapping Epics, User Stories and Use Cases across Systems of Interest Tier 1.

States and States Transitions

States Definition for Automation and Performance

Systematic automation of a process requires contextual enrichment of the information flowing within and across the subsystems within the process. Within the drilling process, many facets to this contextual enrichment need to be available systematically. It is possible to model these contexts as a series of states (such as tripping, drilling, cementing, and so on).

This “state machine” concept of the drilling process is fundamental to drilling systems automation and all tasks, models and activities during drilling correlate with the current state of the drilling process. Consequently, it is critical that the current state be well known and communicated to all users and that the transition to a new state be broadcast simultaneously to all users in real time.

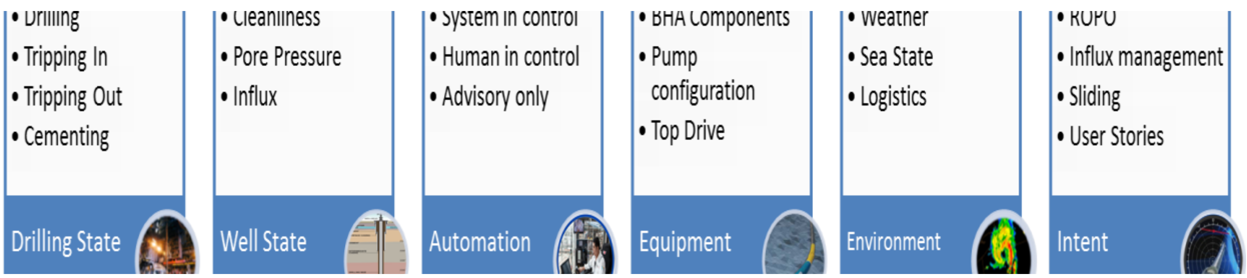

Figure 19 - Overview of States Relevant to Drilling Systems Automation

Historically, the operational state has been defined by the observation of the operation in progress and as reported in the daily drilling report. This method is low fidelity; detail is lacking because humans tend to smooth out the observations. A typical example is the manually written, low-resolution IADC Drilling report.

An automated distinction of states at a high resolution is required for automation and for detailed operations analysis. The distinction between low resolution and high resolution of states is the distinction between grouping multiple states under one heading with timing to the nearest quarter-hour versus identifying all states to the nearest second.

The Wellsite Information Standard (WITS) recommended the transmission of operational state (rig activity codes) by computer systems during drilling, although they had been in use since at least the late 1970s.[11] WITS records depend on two criteria: the rig-activity code and the required interval of the record. The actual drilling operation (rig activity) can be automatically determined by digitally monitoring the hoisting, rotating or circulating systems. The need for such a determination is readily apparent if one considers the calculation of rate-of-penetration

(ROP) from measured block velocity. ROP is only valid if the block moves downwards and the hookload is less than the maximum hookload; when continuous upwards movement of the block is detected, the calculation of ROP is terminated. Accurate knowledge of the drilling operation state is also valuable in determining true performance and enabling the correct operation of an automated system.

Conceptually, the hierarchy of well construction states for drilling systems automation include: operation, well, automation, equipment and environmental states.
A fully automated system is expected to know its state because it commands the actions of the machines. A manual system requires a state engine to determine the states as they occur for accurate tracking and communication of state. As manual systems transition through degrees of automation to highly automated, the method used to announce the state will transition from state engines and humans to the automated control system.

Operations (Drilling and Completion) States

Operation states are the explicit definition of the operation underway at any given time, regardless of how short or how frequently these states change from one to another. They include all the activities involved in the construction of the well from spud until rig release after completion.

Currently, relatively well-defined states exist for rig activities, while those for other operations, such as preparing muds, wireline, completions, running casing, cementing and so on, are less well defined. Drilling states have focused on operations involving the drill string, automatically determined by sensing rotation, raising or lowering the blocks, mud circulation, etc. The calculation of 18 rig states during drilling based on four measurement channels (traveling block position, hook load, torque and pressure) is shown in Table 2.[12]

Comment	Input ▲	block	bottom	pump	rotate	slips	absent	classified	datagap
Rotary Drill	0	slow	onbottom	on	on	notslips	no	yes	no
Slide Drill	1	slow	onbottom	on	off	notslips	no	yes	no
InSlips	2	...	offbottom	...	...	inslips	no	yes	no
Ream	3	down	offbottom	on	on	notslips	no	yes	no
Run In, Pump	4	down	offbottom	on	off	notslips	no	yes	no
Run in, Rotate	5	down	offbottom	off	on	notslips	no	yes	no
Run In	6	down	offbottom	off	off	notslips	no	yes	no
Back Ream	7	up	offbottom	on	on	notslips	no	yes	no
Pull Up, Pump	8	up	offbottom	on	off	notslips	no	yes	no
Pull Up, Rotate	9	up	offbottom	off	on	notslips	no	yes	no
Pull Up	10	up	offbottom	off	off	notslips	no	yes	no
Rotate, Pump	11	stop	offbottom	on	on	notslips	no	yes	no
Pump	12	stop	offbottom	on	off	notslips	no	yes	no
Rotate	13	stop	offbottom	off	on	notslips	no	yes	no
Stationary	14	stop	offbottom	off	off	notslips	no	yes	no
Unclassified	15	...	...	...	...	...	no	no	no
Absent	16	...	...	...	...	...	yes	yes	no
Data Gap	17	...	...	...	...	...	no	yes	yes

Table 2 - Examples of Drilling States

Computation of the rig states from patterns in surface measurements may involve complex and stochastic methods. For DSA it is more important to define rig states as finite states that can enable automation. The actual real-time computation of the states is left to commercial engines which will require verification and validation for confidence in their abilities.

Figure 20 shows a generic, highly simplified, finite-state drilling model that consists of repetitively running pipe (trip in), repetitively drilling, repetitively pulling pipe (trip out) and performing some operation, such as changing the bit or the BHA, and then tripping back in.

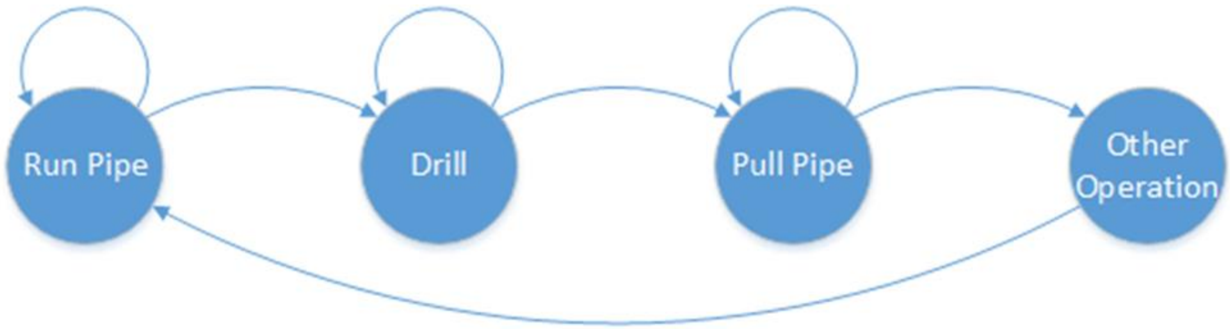

Figure 20 - High-level finite state machine describing the drilling operation

The drilling state is composed of several states that might depend on hardware configuration.

Figure 21 is an exploded finite-state machine (FSM) of the run-in-hole operation. For example, one of the activities listed in Table 2 is slide drilling, which assumes that a drilling motor is in use downhole. The left-hand columns of Table 2 form a truth table and indicating the drilling states forms an FSM.

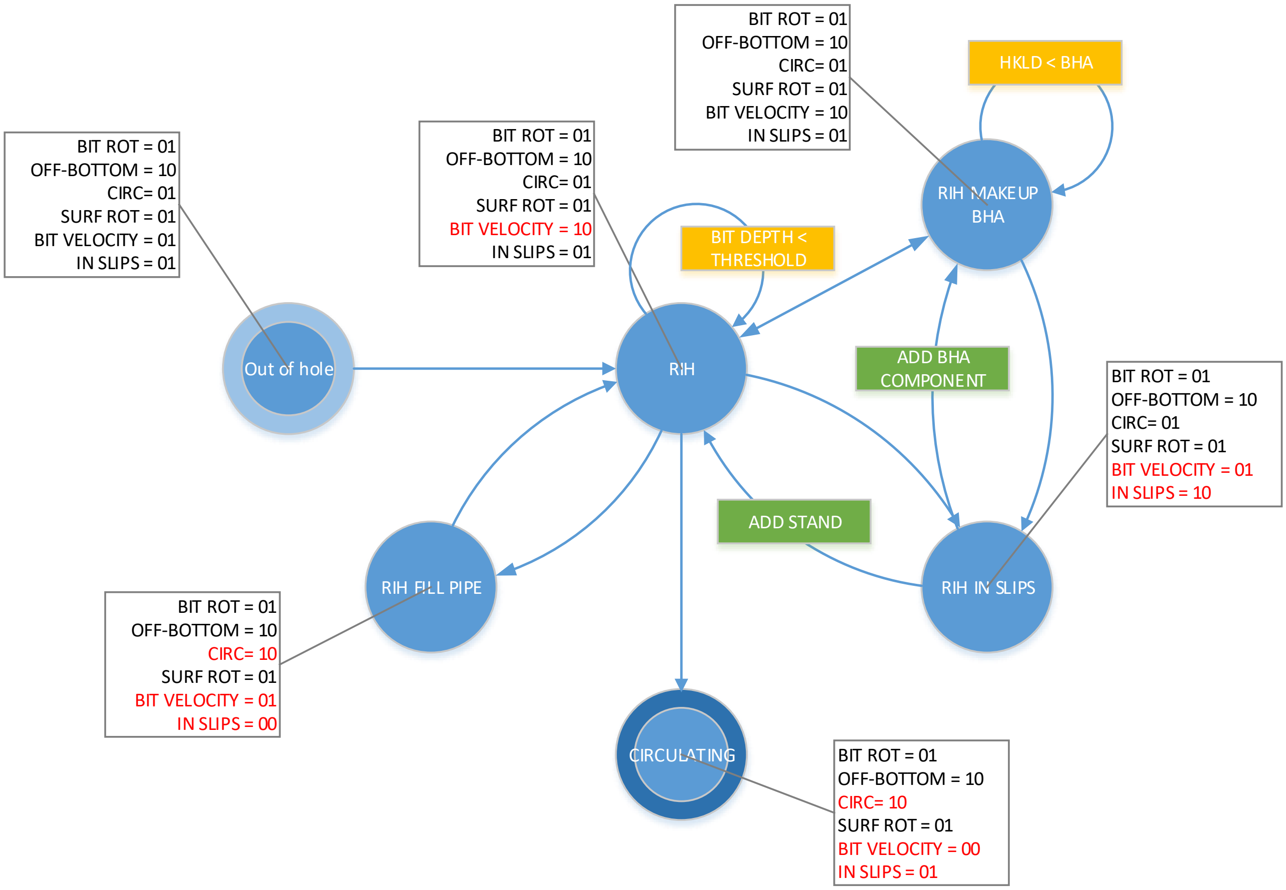

Figure 21 - Example of an FSM of the Run-In-Hole operation; states of critical items are given by two-bits, where 00 is not relevant, 01 is off, 10 is true positive, and 11 is true negative. The start state is Out-of-Hole and the end state is Circulating-off-Bottom (note that Bit Depth > Threshold)

A significant issue with an FSM is the definition of state transitions, which for an automated system is the time when models and controls are changed. Although the states are possibly well defined, the transitions are problematic. It may be necessary to increase the level of reliable measurements or the level of the physics-based modeling underlying the detection of a change in drilling state.[12]

Table 2 is a truncated list of rig-activities. However, additional states may require manual triggering rather than automatic state detection or advanced automated video graphic analysis. Enhancements could include:

- Nipple up
- Pressure test
- Install wellhead
- Cementing pre-circulation,
- Displace, drop plug,
- Chase cement

- WOC + parallel activities

In the event of parallel paths, the parallel states must be known and monitored. A delay in a non-critical path activity could result in a new critical path sequence of activities that change the primary activity. In delivering value from automation, there will be parallel path activities that require tracking to ensure they will be completed outside the critical path and to know if a delay causes them to become the critical path.

Well States

Well states define the condition in the borehole, including the condition of the borehole wall. These states are typically retroactivity assessed by human analysis; drilling systems automation will require real-time definition throughout the drilling and completion operation so that the automation control system can take correct actions. Currently available technology can measure some of these states, while advanced applications of technology can detect others. Some environments are inaccessible to sensors and require models. A primary example of the latter situation is assessing the condition of the fluid in the wellbore and the state of the borehole wall when the drill string is out of the wellbore.

Unlike operational states, well states are probabilistic; a probability exists that the diagnosed well state is correct. The probability of a correct diagnosis increases with more measurements close to the location of the event and with higher fidelity models, both of which come at a cost to the operation.

Well states have a hierarchical impact on automated operations, from primary control in the event of a flowing well, to insignificant control for minor wellbore intrusion. For example, managed pressure drilling (MPD) automation readily detects small influxes and controls them while drilling ahead. At the opposite extreme, with conventional open-hole drilling and no downhole instrumentation, a small influx may rapidly become a significant event.

The real-time determination of a well state is an ongoing technical opportunity. Measurement systems, such as downhole dynamics tools, can yield significant information on the quality of the borehole because bending moment directly yields information on dogleg severity.[13] Surface measurements can indicate how clean the borehole is by logging cuttings flow, or by detecting cuttings coming across the shaker. However, the quality of surface cuttings and fluid properties measurements are too poor for automation.

Advances are being made as technology applications are researched to ascertain cuttings flow and drilling fluids rheology in real time. Furthermore, application of technology, such as MPD, can provide enhanced measurement of well state beyond the primary application of that technology.[14] Well-state detection from current technologies is an opportunity to further add value in drilling performance and automation.

All well states are defined by time but must be correlated to depth, as is measurement while drilling (MWD) and logging while drilling (LWD) data. This enables the automated system to know what action to take at any depth in the borehole based on past data (last trip) and current data (current trip), such as drilling torque.

Tabulation of typical well conditions and parameters for an automated system include:

- Borehole diameter at any interval
- Borehole effective diameter at any interval[15]
- Borehole tortuosity
- Fluid losses to formation—where / depth
- Fluid gains from formation—where / depth
- Borehole cleaning, cuttings bed build-up
- Ballooning—growth and retraction of borehole diameter
- Breathing—losses with gains that are non-permanent
- Borehole pressure gradient
- Formation pore pressure gradient
- Formation fracture gradient
- Rock strength along borehole—assessing potential ROP as well as steerability
- Lithology column

Knowing the well condition, and hence the well state, enables the automation system to avoid operating outside the stable envelope, which causes deterioration of the borehole condition up to and including stuck pipe events.[16]

Automation States

Automation states define the controlling system at any time. Because several controlling software programs and systems are involved, possibly from various companies, there is a hierarchy of automation control.[17] To function properly, the automated drilling system must know the state of automation and dependencies at all times.

Consider the following example: the bit is on-bottom and drilling with an engaged drilling control system designed to optimize rate of penetration. Another automated system, running at a monitoring level, detects a possible influx. The priority for an influx is higher than the priority for optimized drilling, so the automation state is transitioned from on-bottom drilling to pick-up off-bottom, which invokes the block speed automation to avoid swabbing the borehole, and then to stationary with no circulation or rotation to check for flow automatically.

This example points to the need for controlling logic that shifts priority and execution among automation routines as it transitions to various states. Regardless, each automated routine or entity must be able to signal its state so that the controlling logic and the operator can correctly control the operation. Furthermore, the system must be able to broadcast the automation state and changes in the automation state to all operations performing in the automated system at any level. This broadcast relates as well as to human operator performing in interactive mode through supervisory control, so the operator is as aware of the situation as the automation system.

Equipment States

Equipment states define the capability and the condition of equipment and machinery needed to undertake planned operations. These states include such elements as capacity, minimum and maximum rate, failure probability, maintenance interval, current efficiency and any degradation trends. They also include condition monitoring and the ability to predict needed maintenance of components downhole or on surface. The BHA in the hole at any time is a good example of equipment state.

In the example of a mud motor, the automation system needs to know more than whether the motor is present and that slide drilling is an option. It also requires further equipment information to execute the slide properly. For example, it must have information on:

- BHA Components
    - Mud Motor is present
        - Maximum weight
        - Maximum pull
        - Flow range
        - Revolution per gallon
        - Maximum differential pressure
        - Stall differential pressure
        - Torque at maximum differential pressure

Environment States

Environment states are the effect of weather, supply chain and other external impacts that dictate the operations the automation system ought to implement. This is at a very-high level, but severe weather may dictate suspension of operations, or the failure to deliver equipment or materials may cause the automation system to initiate a change in the action sequence. In an intelligent system, understanding not just the objectives and equipment capabilities, but the external constraints that affect the ability to function effectively, are critical to the optimal performance of the system.

Intent States

An important state, often forgotten when considering systematic automation of any process, is the intent of the system and what it is trying to achieve. If the automation system is to integrate seamlessly with its subsystems, including the human in the loop, then it also needs to understand what the process is trying to achieve. For example, the driller may be trying to ramp up flow to crack open a drill string valve or ramping up flow to break the gel, which are very similar processes with different objectives.

To seamlessly integrate functions across the control landscape, the automation system needs to understand the objective of the action. A key element in managing intent is the development of well-defined situations that form the basis of the integrated automation system. In Figure 18 this is called User Stories. In fact, this is a hierarchy that maps system needs to capabilities and intent.

Systems of Interest Descriptions – Functionality, Evolution, Technology and Skills Forecast, States Transitions

System of Interest functions describe the output each system of interest delivers which defines the necessities for automating the system.

Bottom Hole Assembly System of Interest

The BHA System comprises two key sub systems:

- Bit/Rock interaction
- Well bore steering

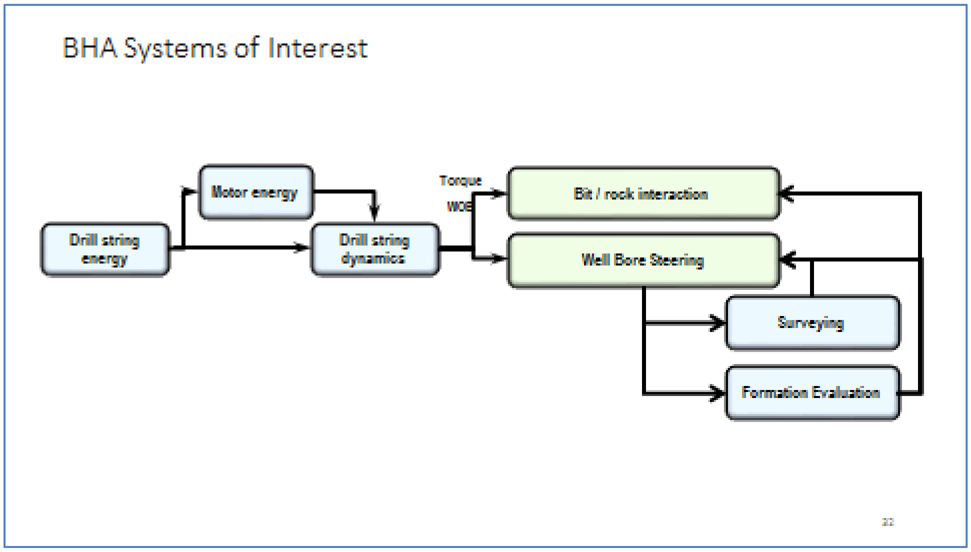

Figure 22 - BHA System of Interest

Bit/rock interaction subsystem of interest

Bit/rock interaction is the system that transforms energy from the drill string and fluids system to progress the borehole. The bit/rock system, and its interaction with interconnected systems, create the primary rate-of-progress driver for deepening the borehole. The rate of progress is impacted directly by:

- The energy input from the drill string system, the energy input from the fluids system as hydraulic drill bit face energy and downhole motor energy (if present)
- The design of the bit and its interaction with the rock being drilled
- The weight on bit being applied through the drill string system
- The torque imparted to the drill bit and the dynamics of the bit.

The bit/BHA dynamic behavior impacts the transfer of energy to the bit/rock interaction as well as the energy impacted to the borehole wall which can lead to borehole wall failure.

Well bore steering

Wellbore steering is critical to success. because it is primarily aimed at landing the productive section of the well in the best reservoir location for maximum value through the production life cycle. This can involve a designer well bore path that avoids interception with other wells (producing) and obstacles (fault planes) to enter the reservoir at the desired location and trajectory. This steering of the wellbore path is solely a steering domain and not a reservoir domain. Borehole steering currently has two key options: a stand-alone downhole robotic system that functions in rotary drilling mode (Rotary Steerable System) or a surface driven sliding and rotating method that is operated from the hoisting and rotating system and incorporates a bent housing mud motor in the BHA system.

The BHA system is active through the epic of 'drill a stand.'

System of Interest	Bottom Hole Assembly System		
Functionality Description	Transfer power and weight to the bit, steer the borehole path, reduce drilling dysfunction, measure and transmit drilling and well bore data from downhole to surface		
	Primary	**Secondary**	**Tertiary**
Deliverables	Weight on bit Steering borehole	Data acquisition and transmission	
Capability			
Operational concept			
States Knowledge	Drilling state	Wellbore state	
States Transition	Wellbore state (stable to unstable / clean to not clean)		
Human / machine roles	Downhole robotics autonomous Surface hoisting and rotating input	Surface input: - Low data rate telemetry – human (supervisory) - High data rate telemetry - automated	

Table 3 - BHA Systems of Interest

Drill string System

As DSA advances, drill strings will become more intelligent. Drill strings will bifurcate into two groups: the hardwired drills stings with high data rate capability, which in some cases will include power down capability, and other data transmissions methods, which will improve to some 100 bps from current speeds. Hardwired drill strings will collect more along-string data from subs placed intermittently along their length; these include wellbore data, fluids data and drill string physics data.

Wellbore data will enhance the systems analysis of the wellbore condition from which immediate and next well improvement actions may be made. Fluids data will enable improved analysis of the mud stream characteristics as it circulates out of the wellbore, providing input data to the fluid's treatment facility. The drillstring physics data will enhance the understanding of torque and drag and provide insight for well profile as well as energy management. Furthermore, these data will enhance depth corrections for the drill string, which will improve the along-hole position of wellbore data. Non-hardwired drill strings will add similar capabilities with low data rates in real time and high frequency data from internal memories. Memory download will speed up and move off the critical path such that it creates little interference with drilling performance.

As DSA progresses, it will be able to absorb, process and action a large amount of real time data, which is very difficult for a human-controlled drilling operation. The difficulty is created by the challenges of communicating the process data to the human operator and reliance on the operator to continuously use displayed data in a systematic manner.

Hardwired drill strings will more commonly become included 'rig equipment' on deepwater drilling vessels and high-end modern jack-up rigs to differentiate these units for drilling wells that require large volumes of real-time downhole and wellbore data.

Drill string energy to the BHA

Measurements of the energy input and output from the drill string, including energy losses along the wellbore, will enable the Drilling Energy Management System to tune the operation of the drill string to optimize drilling performance. Analysis of these data will lead to changed practices in subsequent wells that will result in reduce energy losses.

Drill string dynamics

Drill string measurements provide data to adjust surface parameters with the goal of minimizing dysfunction from or driven into the drill string. Dysfunction causes loss of energy transmission to the BHA, which reduces ROP. The hardwired system will provide real-time automated adjustment, while the non-hardwire systems will provide intermittent update with significant learnings for next operations from downloaded high frequency data.

System of Interest	Drill String		
Functionality Description	Transfer power and weight to BHA and measure and transmit along string well bore data to surface		
	Primary	**Secondary**	**Tertiary**
Deliverables	Rotation, hydraulics, raising and lowering	Data acquisition and transmission	
Capability			
Operational concept			
States Knowledge	Drilling state	Wellbore state	
States Transition	One state to another	Wellbore state (stable to unstable / clean to not clean)	
Human / machine roles	Downhole robotics autonomous	Surface input:	

	Surface hoisting and rotating input	- Low data rate telemetry – human (supervisory) - High data rate telemetry - automated	

Table 4 - Drill string System of Interest

Well Control System / Managed Pressure Drilling (MPD) System

The adoption of MPD systems is advancing both offshore and on land. Initially billed as a way to "drill the undrillable well," MPD systems are becoming recognized as a system to manage a well in a closed manner and, on offshore rigs, are progressing as a tool to reduce risks. Onshore rig installations began as a tool for improved drilling performance through reduced chip hold down pressure by drilling with mud weights closer to pore pressure but are graduating to a tool to reduce insurance costs. MPD is transitioning to a continuous well control system as the industry adopts it as an automated well control method. It is anticipated that MPD systems as automated well control systems will become ubiquitous across the global drilling fleet.

Well Profile Management

As the length and complexity of wells advances to access and penetrate reservoirs in optimal manner for productivity, well profile management has become critical. Well profiles include all aspects of the well bore, from trajectory (the planed path), the path (the actual path), the tortuosity (the path curvatures), the bore rugosity (the surface undulations of the wellbore), and other aspects that collectively define the true shape of the wellbore.

The value of understanding the full attributes of the well profile include benefits, such as improved torque and drag analysis, improved mud flow analysis and its effect on bore hole cleaning, improved placement of downhole equipment, such as ESPs, and improved production flow from the well bore. Profile management has a life cycle impact commencing with drilling efficiency, through production operations and operating costs, and culminating in well abandonment.

Trajectory includes:

- Well placement tortuosity
    - major (Dog Leg Severity)
    - micro (high resolution)

Wellbore Management includes:

- Pore pressure
- Hole cleaning
- Stability
- Quality

Drilling Energy Management includes:

- Drilling energy management is a process SoI covering
    - Input
    - Loss
    - application of energy in the drilling process.
- Drilling Dynamics
- ROP Maximization
- Hydraulics

Fluids System

The fluids system is viewed as two subsystems: fluids preparation, treatment and pumping, and solids control and waste management. Fluids systems have undergone little change over the years in terms of sensors and treatment processes. Some equipment changes include controllable centrifuges and variable frequency drive shakers that provide an opportunity for control.

The advent of MPD has brought sensor improvements in terms of online real time measurements, such as mass flow from Coriolis meters. These have proven to be costly installations that have therefore not been taken up in normal mud operations. Adding sensors and controllers to valves becomes an expensive proposition, especially on land where the number of valves can be very large and the maintenance costly because of regular rig moves.

Offshore systems have been installed that allow recipes to be programmed into a bulk dispensing system to dispense the desired fluid constituents. Mud systems present an enormous opportunity to apply automation. However, progress has been extremely limited, and the primary barrier is a lack of cost-effective sensors.

Fluids preparation, treatment and pumping

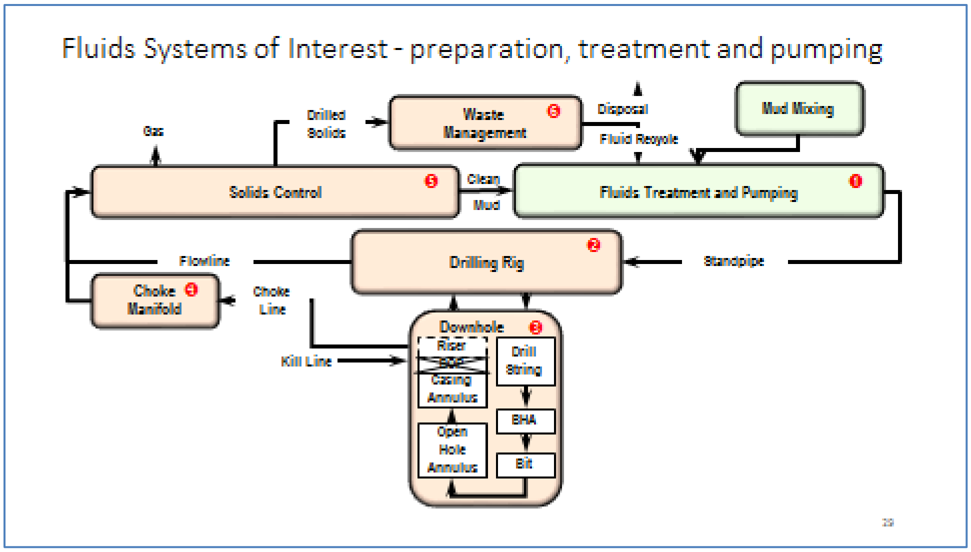

Figure 21 – Mud Preparation Schematic[18]

Solids control, waste management

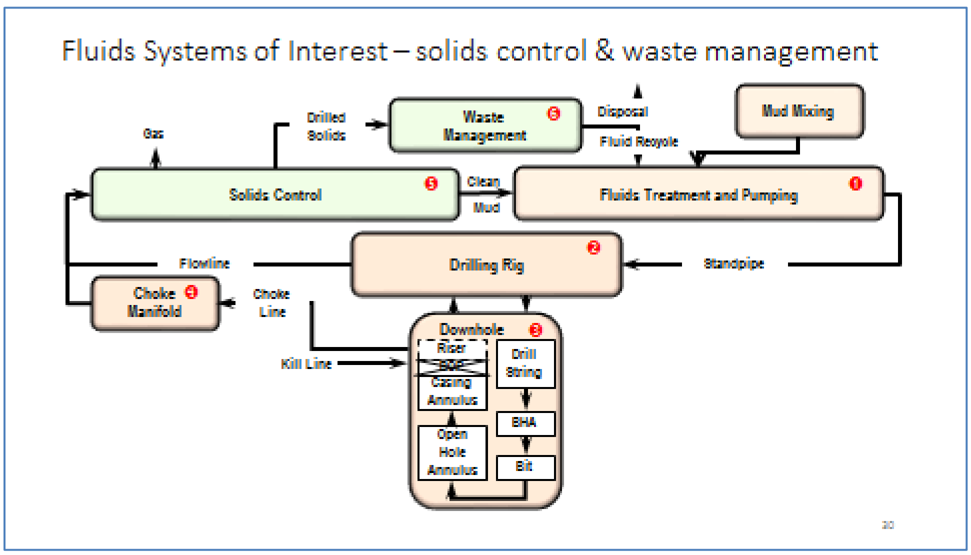

Figure 22 - Solids Control and Waste Management Schematic[18]

Rig System

- Hoisting and rotating
- Pipe handling system
- Power supply
- Positioning

Drilling Crew

- Rig Crew
- Directional Crew
- Fluids Crew
- Data Acquisition Crew

Information System

- Downhole data acquisition
- Surface data acquisition surface
- Wireline Logging
- Communications
- Aggregator/Historian
- Human Machine Interface—Display

Completion System

- Cementing
- Casing
- Wellhead
- Well Flow Control
  - Packers
  - Downhole Pumps
- Well Intervention
  - Slickline
  - Coiled Tubing
- Reservoir Stimulation
  - Fracturing
  - Acidizing

Capability Viewpoint (CV)

CV-1 Vision

By 2025, multiple repeatable land well plans will be uploaded into an interoperable drilling system that automatically delivers a quality well bore into the best geological or reservoir location, install the casing and zonal isolation required to provide well integrity, and install the completion system that enables production of hydrocarbons in an efficient and cost effective manner.

This automated system will update remote operators and experts in real time to changes in all aspects of the situation and will identify potential paths for success that experts may use to input control. Routine multiple wells will rely on remote operations centers to monitor progress and react to alarms.

By 2025, single, complex, deepwater, deep wells having a high degree of lithological uncertainty will rely heavily on advanced automated systems with supervisory control to deliver safety, performance and quality wells that maximize production value. These challenging operations will rely upon onsite and remote centers of excellence to provide real-time and near real-time analyses updates.

These two ends of the pattern of drilling and completion operations for oil and gas wells define the breadth to which the reference architecture must apply and provide the boundaries of the individual pattern architectures that will articulate specific operations and well design. Well categories can be classified according to subsurface uncertainty.

Development wells typically have low uncertainties in subsurface models. Appraisal wells have some degree of uncertainty because they are being drilled to prove subsurface models and may encounter a different situation than the one envisaged. Exploration wells have high degrees of subsurface uncertainty because they are being drilled to prove or disprove a hypothesis.

Pattern architectures are expected to include specific steps in the graduation from repeatable land wells to deep offshore exploration wells, which have distinctions between them that include:

- Multiple repeatable land development wells
- Multiple repeatable offshore platform development wells
- Single land development wells in well-known area
- Single offshore development wells in well-known area
- Single land appraisal wells
- Single offshore appraisal wells
- Single exploratory land wells
- Single exploratory offshore wells
- Single exploratory deepwater offshore wells

CV-2 Capability Taxonomy

The capabilities required of drilling systems automation are defined in a hierarchy that focuses on quickly and safely delivering low cost, high value wells. Speed of delivery is derived from achieving reduced schedules relative to ultimate potential, or Maximum Theoretical Performance and to offset performance as well as systematically achieving planned times with recognized improvements.[17]

High performance (reduced durations) reduces costs in the time-cost drilling environment as well as enables earlier delivery of hydrocarbons. Achieving planned well times provides a deterministic environment for coordinating activities effectively.

Low cost is an aim of automation that enables oil and gas projects to achieve economic viability at lower oil and gas prices and enables a project to achieve funding in competition with an alternative project. Automation has started to realize direct cost savings through reduction of onsite personnel and has enabled personnel to take supervisory control roles in which they can supervise multiple operations.

High value is derived from functionality that leads to or achieves designed parameters in terms of production potential. High value can also be developed from analysis during the drilling operations. High value includes life cycles costs in the form of production (lifting) costs and cost-effective well maintenance. One example is reduced wellbore tortuosity through high frequency steering input, which leads to less wear and tear on production systems and, in horizontal wells, less liquid drop out-reduced well flow.

Pattern architecture offers some distinctions in terms of value delivery through:

- Exploration activity valuing formation data acquisition that leads to subsurface interpretation
- Appraisal activity valuing formation data acquisition that leads to subsurface interpretation and hydrocarbon productivity testing
- Development activity valuing cost effective well hydrocarbon productivity in near and long term.

The DSA Roadmap targeted for 2025 is based on the original vision developed in 2012; in 2025 there is an expectation that significant market penetration of drilling systems automation can be accomplished. Both drivers and inhibitors exist for the rate of development and adoption.

Drivers include:

- Industry expectation, based on early applications, that automation will improve the drilling and completion operations in terms of schedule and quality
- Industry experience that advanced control and automation loops have successfully accomplished tasks, such as dynamic positioning of offshore vessels, rotary steering of wells using downhole systems (robotics), high frequency steering updates from surface systems and advanced MPD systems, that are not possible by humans.

Inhibitors include:

- A drive by industry organizations to develop proprietary systems and resist open architecture. This approach allows conglomerates to dominate the arena initially and potentially in the long term with detrimental effects on overall industry performance and automation application. Industrial automation development in the 1990s through the so called 'field bus wars' demonstrated that the drivers of adoption were those companies that supported and implemented an open architecture view in which systems collaborate through standards and compete through innovation. This industrial automation transformation provides a strong insight to the value and impact of industry defined interoperability.
- Lack of interoperability leads to very significant installation costs and long lead times that are repeated over many installations. The industry initiative which created an oil and gas standard for interfacing the Subsea Production Control System (SPCS) with a Master Control Station (MCS) or a Subsea Gateway to the Distributed Control System (DCS) took ten years to accomplish. The OPC Foundation has reported the benefits of this initiative to be some 10% cost savings and some 80% schedule savings.
- Lack of direct payback to the prime investors due to the predominate day rate drilling model. A change in remuneration for technology investments that add value would become an accelerator.

Operational Viewpoint (OV)

OV-1 High-Level Operational Concept Graphic

The high-level textual description of the operational concept.

A highly automated drilling system must deliver high quality well bores in the right location in short cycle times (release to releases). The reference performance against which the benefits of drilling systems automation will be measured has risen in recent years as USA land drillers have achieved performance levels that are close to the Maximum Theoretical Performance (MTP)[19]. Automation technology will need to consistently deliver increments above the MTP, such as:

- Reduced rig footprint by removing humans from the rig floor

- Offline activities undertaken by automated machines, such as stand building that need not wait on available crew
- Short cycle connections that require no crew
- Mud mixing and treatment without human intervention, ensuring short durations that remain off the critical path
- Minimizing drilling dysfunction, leading to higher ROPs and reduced BHA component damage that require trips and repair costs.

Advantages in manufacturing style drilling have been achieved by prebuilding BHAs and premixing muds and other similar centrally located activities. As such, automation at the rig site will have a limited offering for these activities in regions where this central facility has such capability. Automation benefits can then be achieved through applying the automation in the central facility to reduce lead time and cost for preparation.

Detailed scheduling will become an asset in driving value with automation.

Data and Information Viewpoint (DIV)

DIV-1 Conceptual Data Model

The required high-level data concepts and their relationships.

The data and information viewpoint (DIV) have been mapped for drilling systems automation through the progression from the Purdue model, the ISA 95 model, and the overlay of the Manufacturing Execution System. This led to the development of the Drilling Systems Automation Decision and Control framework which can guide the interactions of various levels of data acquisition and processing in accordance with ISA 95.

The adapted reference model is used by the DSA-R to create the decision-making and control framework**.** This framework also provides a map for the relationship of various interrelated systems in the application of DSA. The five levels for well construction identified on the left-hand side of the graphic and listed below correspond to the five layers defined in the ISA reference model.

The DSA Decision Making and Control Framework is a very powerful model that relates the data and information processes of well construction from machine control to enterprise planning. The foundation is derived from the Purdue Model created in 1989 for a Computer Integrated Manufacturing Model.[20] The Purdue Model shown in Figure 25 was created to improve the

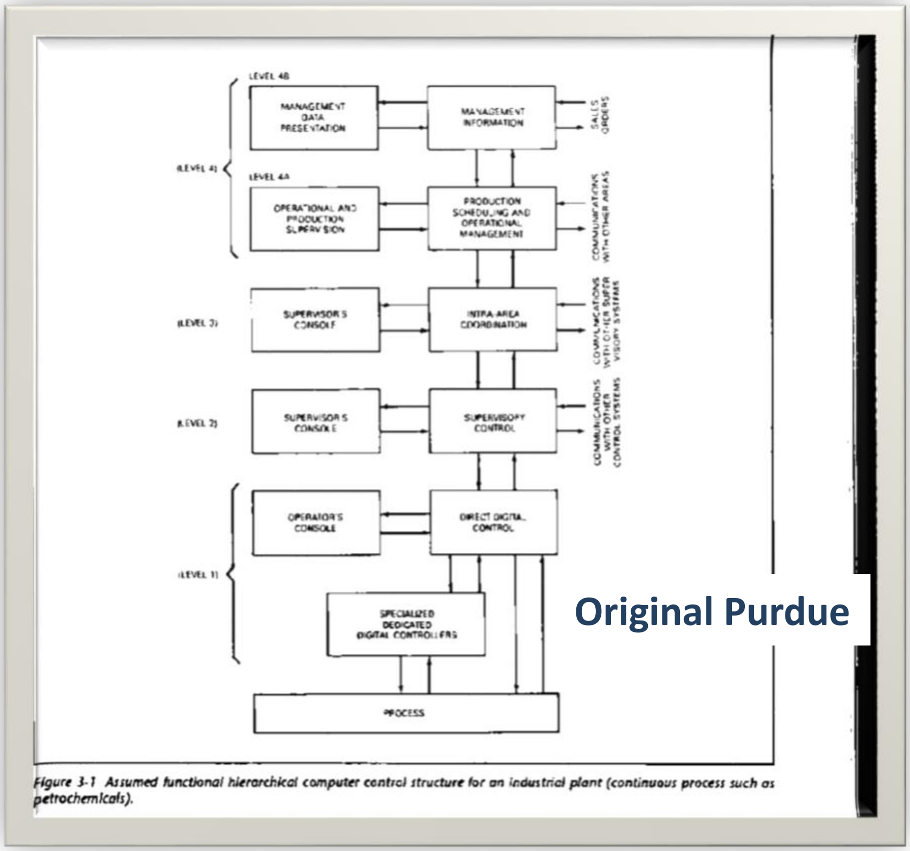

Figure 3-1 Assumed functional hierarchical computer control structure for an industrial plant (continuous process such as petrochemicals).

probability that a truly integrated information system could be rapidly achieved through all levels of a manufacturing organization. The model provides a construct of the relationship connecting enterprise decision making to shop floor activities and vice versa.

The International Society of Automation (ISA) developed the details within the hierarchical Purdue Model to improve guidance on application. ISA particularly added interface standards (Figure 26).

Figure 23 - ISA Purdue Model

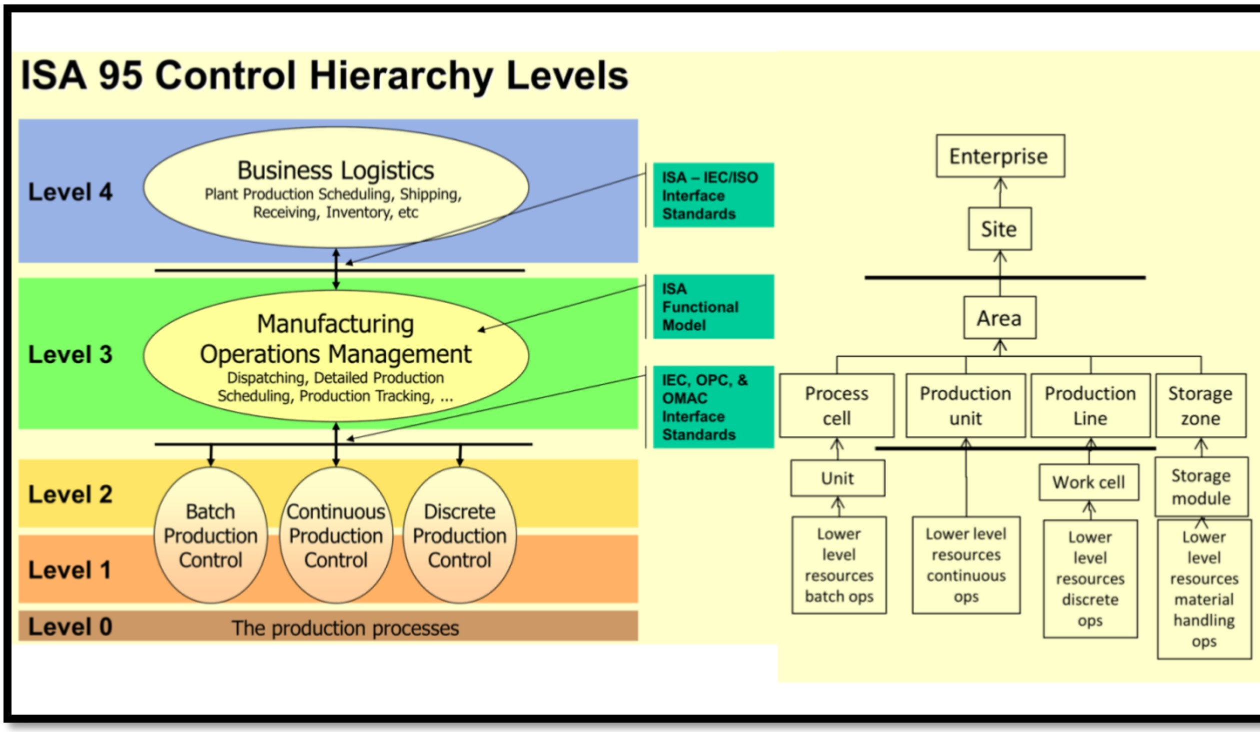

Figure 24 - ISA 95 Control Levels

Applications experts continued the evolution by overlaying the Manufacturing Execution Systems (MES) that connect the higher levels to lower levels through manufacturing flow in design, planning and execution.[21] The mapping of these design, planning and execution work flows through the levels within the ISA-95 hierarchy provided the basis for development of similar workflows for drilling planning and execution.

DSA Decision and Control Framework

The DSA Decision Making and Control Framework (Figure 25) developed from MES, ISA-95 (thus Purdue) is the most current mapping of the ISA-95 five levels for well construction as listed below:

- Level 4 - Enterprise management
  - Managing business-related activities of the drilling operation (business planning and logistics)
- Level 3 - Operations management
  - Managing workflows to drill, protect the hole and complete the well
- Level 2 - Execution management
  - Supervising, monitoring, and controlling the physical processes with real-time controls and software
- Level 1 - Machine control

    - Sensing and manipulating the physical processes.
- Level 0 - Physical processes
    - Defining actual physical processes of the drilling and completion operation (well construction).

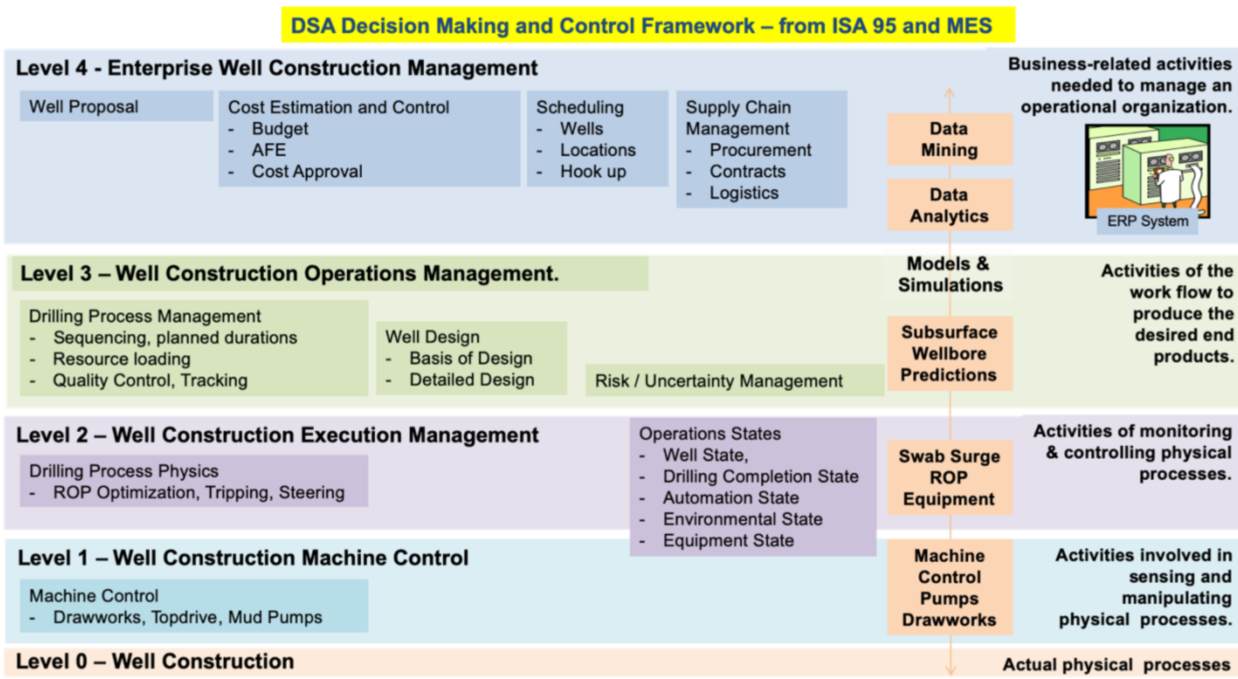

Figure 25 - DSA Decision Making and Control Framework (from ISA 95)

An overlay on this version highlights the work flows in the Well Construction Execution System and Data Acquisition. It also locates the onsite and remote centers relative to the hierarchy (Figure 26). The distinction between control and operations and interpretation and excellence centers is that the former performs in the supervisory control loop and the latter analyzes data to feed new parameters to the former. This distinction is the format adopted by Rio Tinto in their development of automated mining. Rio Tinto's descriptions of each are:

- Operations Center
    - Integrated operations, increased efficiency, better risk management. Rio Tinto's Operations Centre in Perth, Australia, is "Mission Control" for the entire Pilbara iron ore network located 1,300 km to the north. From this one site, more than 400 operators analyze data and synchronize an integrated system in real time, manage 15 mines, 31 pits, four port terminals and a 1,600-km connecting rail network. This increases efficiency, improves reliability, decreases variability and

allows the business to better identify and improve performance across the supply chain.

- Excellence Centers
    - Data access, expert clusters, enhanced productivity. Excellence Centers unite experts with those from partner organizations and give them access to real-time data from operations around the world so they do not have to be on site. These centers allow teams to make better decisions, enhance productivity, and reduce costs. They also improve the safety and wellbeing of our employees by reducing the need to travel to mine sites to share expertise and excellence. [22]

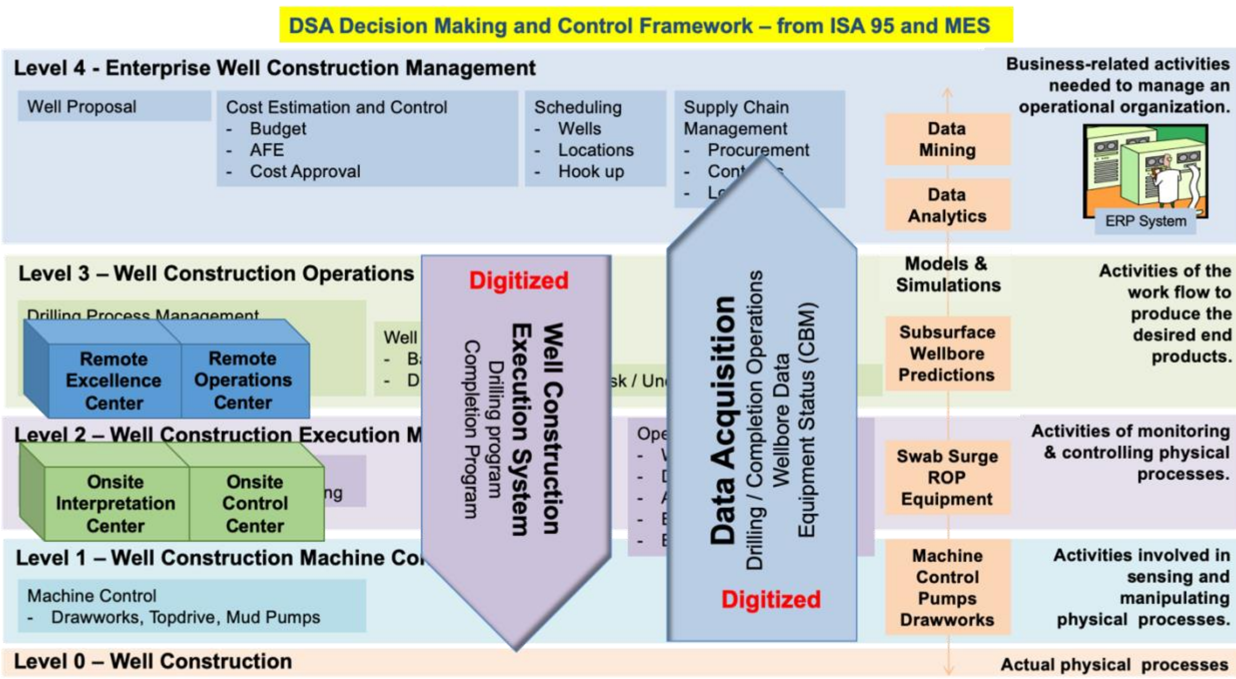

Figure 26 - DSA Decision Making and Control Framework with Work Flows

The levels in the hierarchy operate at different frequencies with the highest frequency in the control mode at level 2 through to the lowest at the information mode at level 4. This DSA framework provides the hierarchy from the proprietary modes of machine control through the control interface transitioning from OPC-UA at the control level to WITSML at the information enterprise level. The OPC-UA/WITSML interface as well as the OPC-UA/DDS interface are currently being mapped by industry teams to enable complete interoperability between these systems.

The status in 2018 is shown in figure 27 where aggregators (combined with historians) are being applied at level 2. At this same level multiple applications are being applied to semi automatically control certain drilling processes. This control occurs at level 2 with machine instruction driving the machines at level 1.

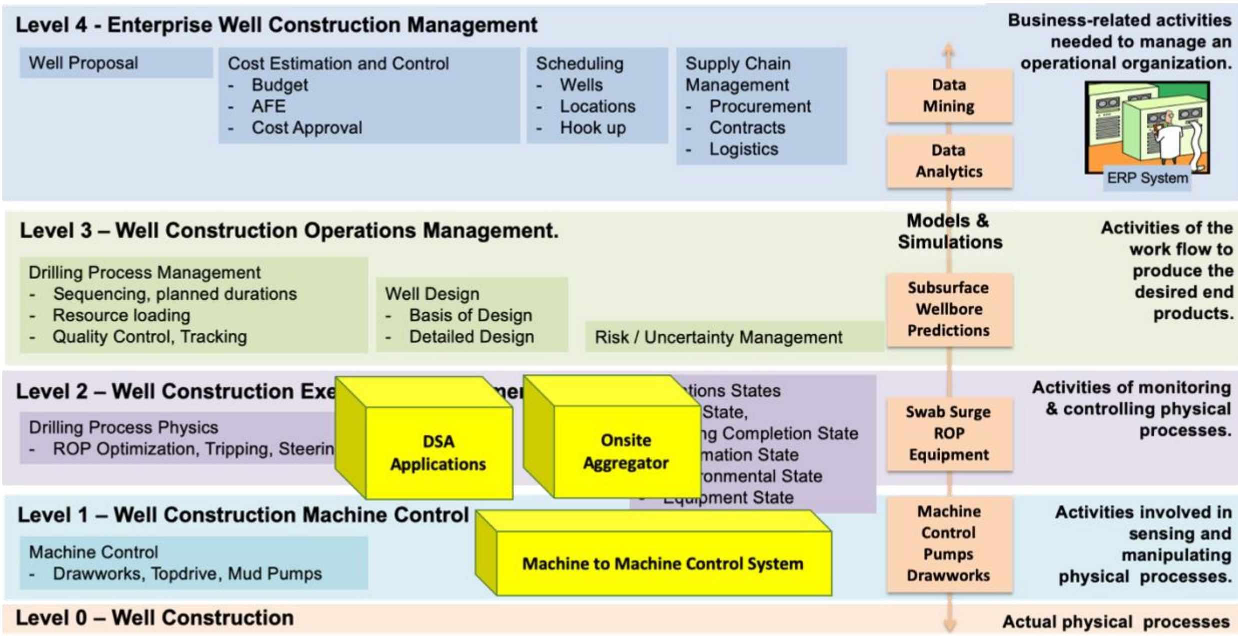

Figure 27 Application of aggregators and applications - year 2019

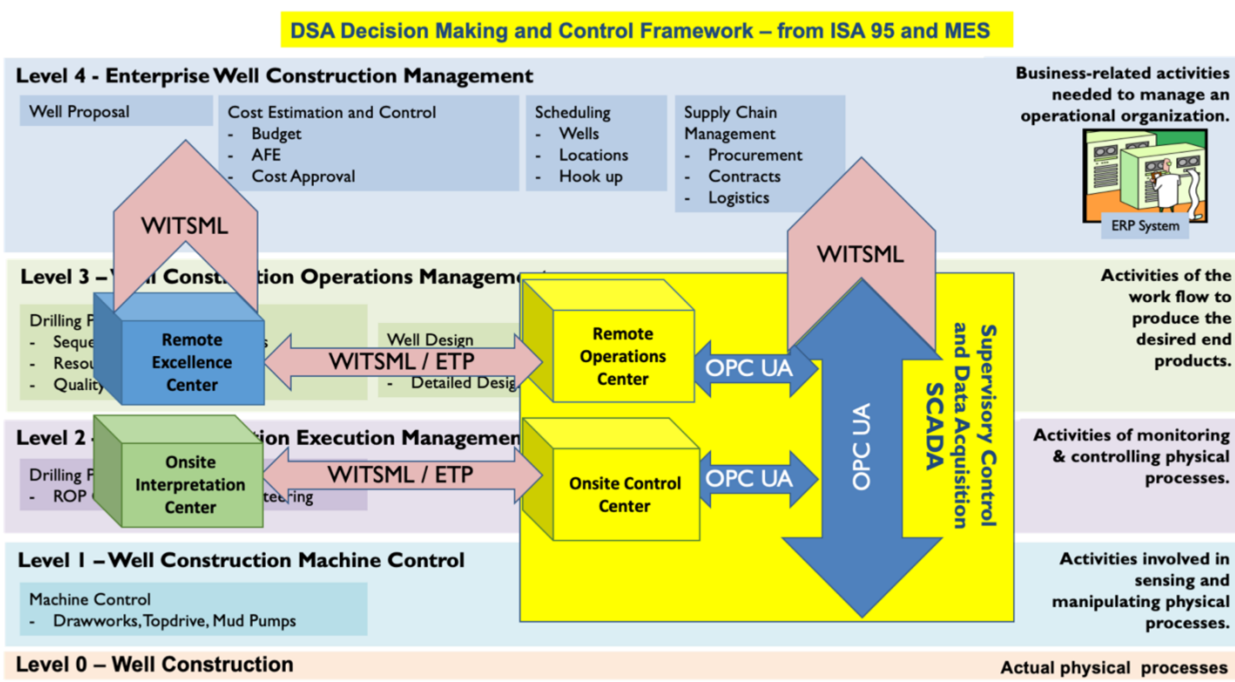

Figure 28 - DSA Decision Making and Control Framework with Future Data Flows

Figure 28 depicts the future state of control data flow and evaluation information through and across the hierarchy, with the Onsite Control Center (OCC) and Remote Operations Centers

(ROC) coalescing into the Supervisory Control and Data Acquisition (SCADA) system. The adoption of OPC UA into the SCADA environment enables full horizontal and vertical integration of the drilling systems control.

At this stage, the onsite control center will be removed from the rig floor and manned by all onsite personnel that effect control over various systems. This means that mud engineers, directional drillers, mud loggers and telemetry operators all share the same data and control room as the driller. This transition will require advancement of the sensors currently employed such that the displayed data truly reflect operating conditions and the driller does not need to ‘see’ the floor, ‘feel’ the vibrations and ‘hear’ the noise. Likewise, the other supervisory personnel will receive data without having to make local, manual and outdated tests, such as mud balance.

The encapsulation of the OCC and the ROC into the SCADA envelope will enable the transition of many onsite roles to offsite roles while the machines and equipment retain workflow and onsite supervision of directions.

The positioning of the Onsite Interpretation Center (OIC) and the Remote Excellence Center (REC) outside the SCADA envelope recognizes that these centers are not in the control loop and operate in an advisory function. Although they could be co-located, it is anticipated that in many cases the Subject Matter Experts (SMEs) that man these centers may be located away from the drill site for the OIC or regionally located, and others may be centrally located for the REC. The smoothness of the operation will be defined by data flow, communications ability and organizational effectiveness.

The DSA Decision and Control Framework model provides the foundation for the development of controls hierarchy in the application of automation and defines the most appropriate decision loops in manual drilling. The use of this framework has not yet been exploited for improving current operations with low levels of automation. Mapping the data acquisition process, analysis, decision making and action implementation through display loops in this hierarchy will add value to all drilling operations including those that employ manual, partial automation and supervisory control of autonomous systems.

DIV-2 Logical Data Model

The documentation of the data requirements and structural business process (activity) rules.

The logical data model at the Reference Architecture level describes the interoperability required to advance drilling systems automation.

DSA-TS developed the proposed Rig Information Model (RIM) to apply real-time drilling information to OPC UA. The primary idea of the RIM was to create a virtual device (e.g., a pump, a top drive, a brake) with a hierarchical information structure that is inherited on creation as described below. The rig is then composed of a list of these devices and objects, which can be modified in real time. The Systems of Interest provide the framework for this hierarchy to be extended beyond 'Drill-a-stand' to all activities associated with constructing a well including both Rig Objects and Well Objects.

RIM Explanation[23]

The Rig Information Model is intended to aggregate all the information about a drilling rig and its wells and expose that information in a standard way. The first step is to separate the physical rig from the wells the rig has drilled. This leads to two major objects—a Rig Object and a Well Object.

A Well Object contains all the information about the borehole. A Rig Object is a component of the rig and is based on the concept of matching the physical devices to their software representation. For example, a Top Drive Object is a Rig Object that is supposed to model the physical top drive, a Drawworks Object models the physical drawworks and a Pumps Object models the physical pumps. Every physical device that composes a drilling rig should have a one-to-one correspondence to its software analog or object.

The Rig Object contains all the device's physical properties, such as its specifications, limits, sensors (measurements) and the results of calculations that are device specific. For example, a mud pump (Mud Pump Object) is a Rig Object that would contain information about the type of pump, the liner diameter and stroke length as specifications, the stroke counter maximum as part of its limits, the pump stroke counter as its measurements and the computed flow rate as part of its calculation.

The Rig Information Model was developed as a method for delivering a consistent data interface for automated drilling applications. As rig configurations vary, this cannot be a static data structure, but must be a framework that will allow the automated drilling application to query the individual rig configuration and determine which data are appropriate for use.
The Rig Information Model, as proposed, goes beyond the realm of rig automation and is an attempt to encapsulate all the data and information about the rig and the well being drilled.

The master object, the Rig Object Type, consists of the Rig Equipment folder. This is a listing of all the Rig Objects, and a Wells Object folder containing information about the borehole, BHA, drill strings, etc., that are part of each well that the rig has drilled. The intent is to deliver any and all information about the current state of the rig and the well it is drilling.

This is a first pass attempt to use a consistent method to expose any information that is currently stored in both the WITS0 specification and the WITSML specification. The proposed Rig Objects meets this objective, but the Well Object is currently not complete and needs further work. As an alternative, operators may use the WITML definitions for well, wellbore, trajectory stations, etc.

To provide simplicity and the ability to browse the structure for any needed data and information, the Rig Information Model is a hierarchical data structure. It is designed to be compatible with an OPC-UA server for platform independence, networked communications (data query and device control) and a standardized software interface.

Rig Object

This template is for any piece of rig hardware. It is an abstracted concept in that there are groupings of information that exist for any rig device. Each Rig Object starts with the template and extends the template with specific information about the device. In object-oriented software terminology, each rig device inherits the structure generic Rig Object and adds its "twist" on the base object. The main elements of a rig object are:

- Specifications
  - static information about each
- Limits
  - a folder containing device limits
- Set Points
  - a folder containing values that may be set to control the operation of the device
- Measurements
  - as folder containing device sensor data for any device
  - contains only real-time values from actual readings
- Calculations
  - a folder containing "processed" information.
- Methods
  - a folder containing values that may be set that controls device operations
  - In combination with the device status folder this is for device control
- Device Status
  - A folder containing three pieces of information

        - Is the device powered
        - Is the device enabled
        - Is the device active
        - Methods may be written to turn the device on and off and enable the device for usage
        - This folder, in conjunction with the Set Points folder is the central location for device control
- Object Type
    - An embedded enumeration to indicate current rig type
- Asset Information
    - A folder containing information on the device's name, model number, serial number and other minutiae about that device
- Maintenance Information
    - How the device has been maintained and when it should be scheduled for service
- Calibration Information
    - Every sensor measurement should contain information about how and when the instrument was last calibrated.
- Device Metadata
    - Additional information about the device or measurement that may be needed for interpretation.

RIM Implementation

Three cases from the spectrum of OPC UA server implementations: an unautomated or normal rig, a partially automated rig, and a fully automated rig.

Unautomated Rig

The most common rig example is unautomated rig. It is still possible to use the Rig Information Model in conjunction with an OPC UA server in order to aggregate data on an unautomated rig. However, there are no methods that will allow for the control of this type rig.

As with other rig data aggregation systems, the main input source will be WITS0. For this case an OPC UA WITS client can be written to decode the WITS stream and aggregate it. It would also be possible to write OPC UA clients for the real-time display of data, which could reduce and simplify the variety of data display screens at the well site.

As OPC UA has a secure, encrypted binary communications stream, this can be used to telemetry the data to operation centers. An OPC UA WITSML client could be written to export the data from the aggregation server (or clone) to already existing data links.
Alarms and events could be implemented, but would probably be pop-up, warning message style. The value add of the Rig Information Model for this case is relatively limited, unless additional data features, like operator logs, daily reports, mud reports and maintenance, are enacted to centralize the acquisition and archival of that metadata.

Partially Automated Rig

Partially automated rigs are currently the industry standard for automated rigs. The value add of the Rig Information Model to these rigs is in its data organization, device control features and flexibility in adapting to the level of automation of any specific rig.

Data organization issues are concerned with having a true real-time data acquisition system in use and the ability to write automation applications with a degree of portability. Whether the rig data are coming directly from device controllers or via WITS0, the amalgamation of data is available to the programmer and application. Data input to the aggregator would probably be a combinations of serial data streams (like WITS0), device controllers embedded in OPC UA objects, and devices which are OPC UA compliant.

For this case, the real effort would be in writing the handlers between the Set Point/Device Status Objects and the individual device controllers. This would allow a standardized method for controlling rig devices and may mediate some of the issues involved with using intermediary PLC controllers.

Depending upon the degree of device control, alarms and events could have additional safety features, like a kick detection response or a lost circulation response.

Fully Automated Rig

This is a dream in which rig components are dynamically replaceable and plug-and-play. If every device on the rig had an embedded OPC UA server (some new controller boards have OPC UA embedded chips in them) that was running the germane portion of the Rig Information Model, then those devices could be discovered and added to the rig aggregation server automatically.

Full data exposure and device control would be built in. It would even be possible to add these devices via a wireless network. That could have a drastic impact on rig up times. Devices could be changed on the fly (hot swapped), with automation software automatically reconfiguring itself to use the new device. Rigs could be constructed using commodity, off-the-shelf parts, and would be quicker and cheaper than current rig construction.

The point is that the technology currently exists to implement this. There, of course, will be teething problems but there is no need to wait for new technology. The Rig Information Model is a first step towards this goal, with the benefits being cheaper, more easily configured rigs drilling better and safer wells.

Drilling Data Hub

NORCE (formerly as IRIS) are generating an approach through the development of a Drilling Data Hub (DDHub).[24] This system is intended to exchange real time data seamlessly between various entities involved in drilling operations. It is an alternative approach to the DSATS RIM and uses a shared drilling semantic model whereby drilling data-producers can expose the meaning of their real-time signals in a computer readable format. Simultaneously, data-consumer applications can discover programmatically those data streams that are the most appropriate for their functioning, which will lead to seamless interoperability.

The semantic framework relies on a few important concepts for the drilling domain. It allows users to qualify the physical quantity associated with the signal, to define its dimensionality and to specify necessary references. Another important notion is the differentiation between measurements, set-points, commands, estimated values, parameters, etc.

Derived measurements are explicitly described as a function of direct measurements. The semantic definition encompasses how signals are related to each other in a semantical network. Relationships between signals and their logical position, in a topological description of the drilling system, are also important.

Finally, the conditional validity of signals may be semantically described. Semantics is a step beyond the more traditional meta data (data about the data) that is tagged to data.

DIV-3 Physical Data Model

The physical implementation format of the Logical Data Model entities, e.g., message formats, file structures, physical schema.

5 of 14: Systems Architecture

This was an initiative attempted by the SPE Drilling Systems Automation Technical Section through the application of OPC UA and through the development of metadata tags for data to become standardized and available for common usage. As with many industry initiatives designed to open systems, it stalled. A follow-on initiative has recently been launched to pursue actions that can enable interoperability.

The intention is that Energistics becomes the holder of any of these standards that are developed and makes them available to the industry. OPC Foundation and Energistics commenced a joint project to connect WITSML and PRODML to OPC-UA May 2016.

This initiative developed a companion specification that connects OPC-UA to WITSML, enabling inter-exchange between the control language (OPC) and the information language (WITSML).

Interrelationship of Viewpoints in Systems Architecture

Combining the various viewpoints creates a graphic of their interdependence. This is an outlook that can drive the future interoperability of DSA.

In 2019, DSA progression is primarily at the subsystems of interest level. These subsystems are growing in application in terms of level of automation. Limited initiatives are encompassing the whole architecture.

Subsystems entry is the affordable and manageable scope for adoption. Unfortunately, without an overview of interdependencies (systems architecture), managing data attributes (see later section) and the need for revised human competency models (see later section), risks of failure will manifestly increase. The industry players will benefit from developing a top down, holistic framework into which the elemental approach of DSA can be adopted.

Figure 31 shows a combined view based on the DoDAF approach to mapping the adoption of a structured system of drilling automation.

5 of 14: Systems Architecture

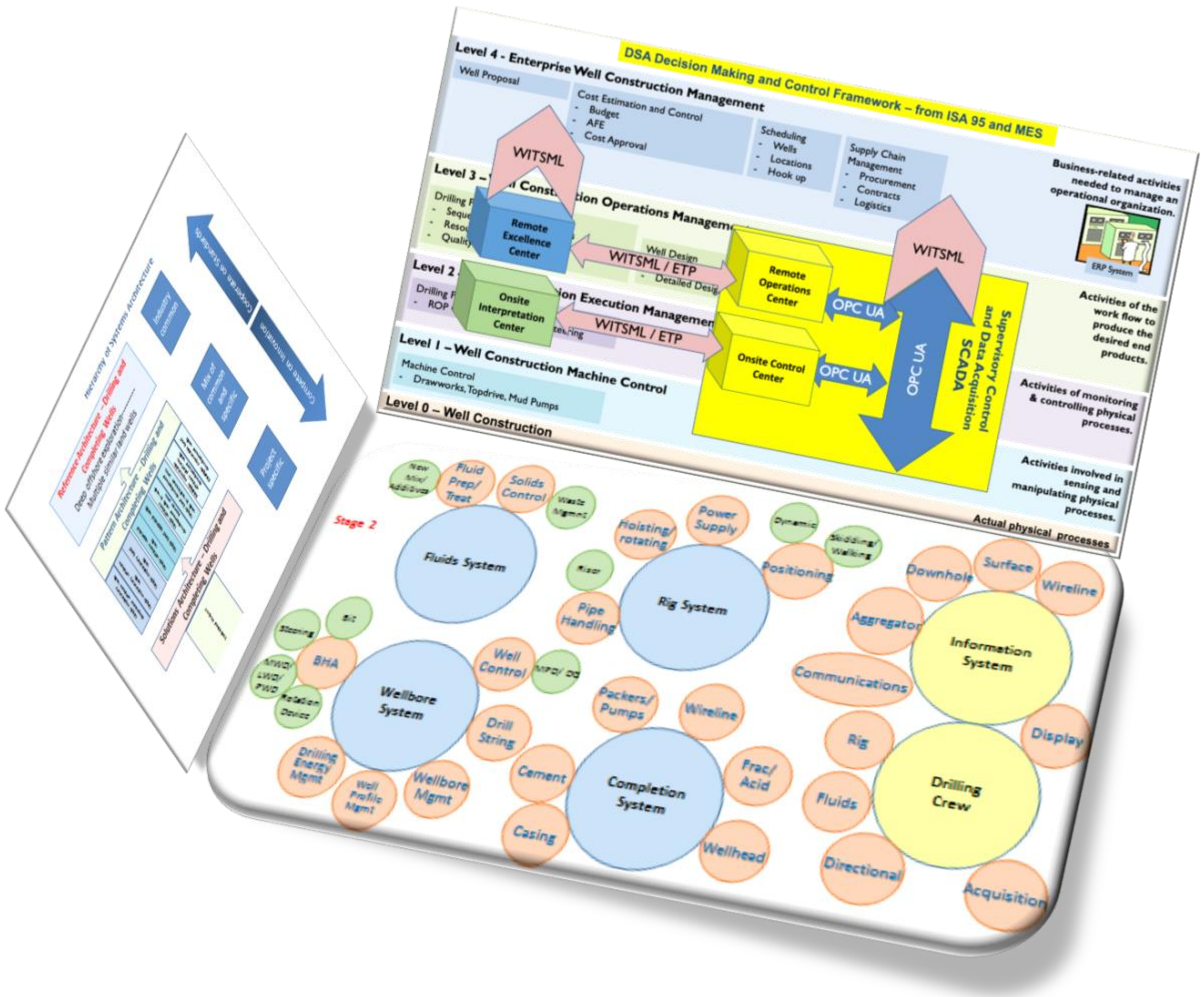

Figure 29 – Combined DoDAF Framework for a Drilling System

Systems Engineering for Solutions Architecture

Introduction

Systems Engineering is a technique commonly used in defense, aerospace, commercial aviation and similar industries to rigorously design and manage complex systems over the lifecycle of those systems. INCOSE defines Systems Engineering as "an interdisciplinary approach and means to enable the realization of successful systems. [Systems Engineering] focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs."

Systems Engineering is a powerful tool for designing and successfully implementing DSA at the Solutions level. It is expected that the highest value DSA solutions will be developed through the application of the Systems Engineering process, the so-called Systems Engineering Vee. Systems Engineering is not routinely applied to the development of complex drilling systems but has been applied by some developers to specific products that are within the Systems of Interest. The lack of application leaves a large gap of opportunity for developing high value and effective DSA.

Systems Engineering can be applied to the collective Systems of Systems for a fully integrated solution or for a System (subsystem) of Interest for a development that's supports a full DSA solution.

Below is a valuable paper describing the application of Systems Engineering. This paper was presented at Deep Offshore Technology (DOT) International Conference & Exhibition in Houston, October 2013 by Calvin Inabinett formerly with Aerojet Rocketdyne. The paper is reproduced in its entirely with the permission of Pennwell, the owner and operator of DOT.[26]

Applying Aerospace-grade Systems and Software Requirements

Verification and Validation Methods to Improve Offshore Drilling Operations Performance and Safety

Abstract

Offshore drilling rigs are increasingly complex integrated systems incorporating automated software-dependent control systems to maintain safe and effective operations. Under even

relatively benign conditions, software issues have caused unintended circumstances, sometimes with catastrophic results. Catastrophic incidents and unplanned downtime are reduced when such systems are based on well-defined requirements that are verified during system development and then validated to work as intended in the operational environments. Industry leaders, governments and international organizations are encouraging more stringent practices to improve offshore drilling operational safety. DNV (Det Norske Veritas) and ABS standards, Integrated Software-Dependent System (ISDS) and Integrated Software Quality Management (ISQM), respectfully, aim to reduce the number of system and software issues through the application of standard software verification and validation (V&V) practices. The aerospace industry has a long tradition of applying such discipline. In fact, it is required when working with some government agencies, such as the FAA and NASA. These disciplines contribute to the design of complex, safe, reliable, high-performance systems that allow humans and equipment to operate in the most extreme environments on Earth and in space. Over the past 11 years, operators in the offshore drilling industry have benefited significantly through application of aerospace-based Systems Engineering disciplines to address a wide variety of high-value rig system safety and performance issues. These processes are most effective when included during development of new rig and subsystem designs. However, significant benefit to system safety and performance can also be achieved when these processes are incorporated as part of service life extension and subsystem upgrade projects. This paper will focus on a description of the processes and benefits that come from applying an integrated system level software requirements verification and validation approach.

Introduction

Safety and Environmental Management Systems (SEMS) activities are at the forefront of today's drilling operations in the Gulf of Mexico. SEMS programs are only as good as the capabilities of the systems they audit. In general, systems engineering activities and methodologies are used to ensure that delivered systems meet customer expectations including system safety and environmental as well as functional and performance requirements. This paper will provide a brief overview of systems engineering with emphasis on verification and validation activities.

The SEMS Code of Federal Regulations (CFR) will then be mapped to a common systems engineering process framework. Finally, a case study will be shown to illustrate how these processes are applied to identify and eliminate and/or control hazardous situations. Systems engineering principles make best possible use of the skills, technologies, and tools available to the marine industry as it faces up to present and future challenges.

Terminology

Verification and Validation. Simply put **Verification** is the act of ensuring that we “built the thing right” while **Validation** is the act of ensuring that we “built the right thing.” No matter what process, methodology, or tools are used to construct a product the success can ultimately only be gauged by validating that customer expectations are met. Verifying throughout the development lifecycle that everything is done per requirements, design, and process gives you the best chance of ending up with a system that is validated by the customer.

Systems Engineering. A system is conceptualized and created to perform a specific task or set of tasks (function) at some rate, in some place or range of places, in a defined manner, for some specific period of time. A system can be small - a watch or a smart phone, or very large, such as a dual activity drill ship or a subsea tie-back system installation. In both cases, large and small, the attributes that describe the system can be identified, and more importantly - quantified. **Requirements** shape the attributes and behaviors of the system.

A **system** consists of **sub-systems**, which consists of **components** (hardware, software, and firmware), including **parts, materials and processes**. Large scale integration of many independent, self-contained systems is referred to as a **System of Systems**.

The **Life Cycle** of a system begins with a need, a concept of something (a system) to satisfy the need, the definition, design, development, test, verification, validation, certification and production of the system, field delivery and commissioning, operations, maintenance and modification (includes repair) of the system, obsolescence, decommissioning and disposal at the end of the useful service life of the system.

Along with consideration of the building blocks above, **Systems Engineering** forms the nexus of the science, the process, the tools, and the rigor to conceptualize, define and develop systems to solve problems from the mundane to the highly critical with the highest probability of first time success. Systems engineering is an interdisciplinary field of engineering that focuses on how to design and manage complex engineering projects over their life cycles.

Systems Engineering

Systems engineering brings structure, discipline and teamwork to large projects and has an increasingly valuable part to play offshore. The Systems engineering approach addresses system risks and interdependencies by bringing together all the disciplines involved, thereby providing a single unified view of the project.

5 of 14: Systems Architecture

Systems engineering has successfully been used for decades to develop aerospace systems to meet the challenges imposed by extreme environments when operating in space. Initiatives to improve the efficiencies, reliability and safety of floating and subsea drilling and production systems are, in many ways, just as challenging.

Lifecycle Processes. A logical overview of the System Engineering Lifecycle Processes is shown in Figure 1. Each one of these processes deserves a separate white paper to describe its fundamentals, science and benefits. This paper will focus on the verification and validation processes. However, all the processes are critical to the success of Systems Engineering.

Technical Processes and Project Processes are summed up by ISO15288:2008 as:

"The Technical Processes are concerned with technical actions throughout the life cycle. They transform the needs of stakeholders first into a product and then, by applying that product, provide a sustainable service, when and where needed in order to achieve customer satisfaction. The Technical Processes are applied in order to create and use a system, whether it is in the form of a model or is a finished product, and they apply at any level in a hierarchy of system structure." [1]

"The Project Processes are concerned with managing the resources and assets allocated by organization management and with applying them to fulfill the agreements into which the organization or organizations enter. They relate to the management of projects, in particular to planning in terms of cost, timescales and achievements, to the checking of actions to ensure that they comply with plans and performance criteria and to the identification and selection of corrective actions that recover shortfalls in progress and achievement." [2]

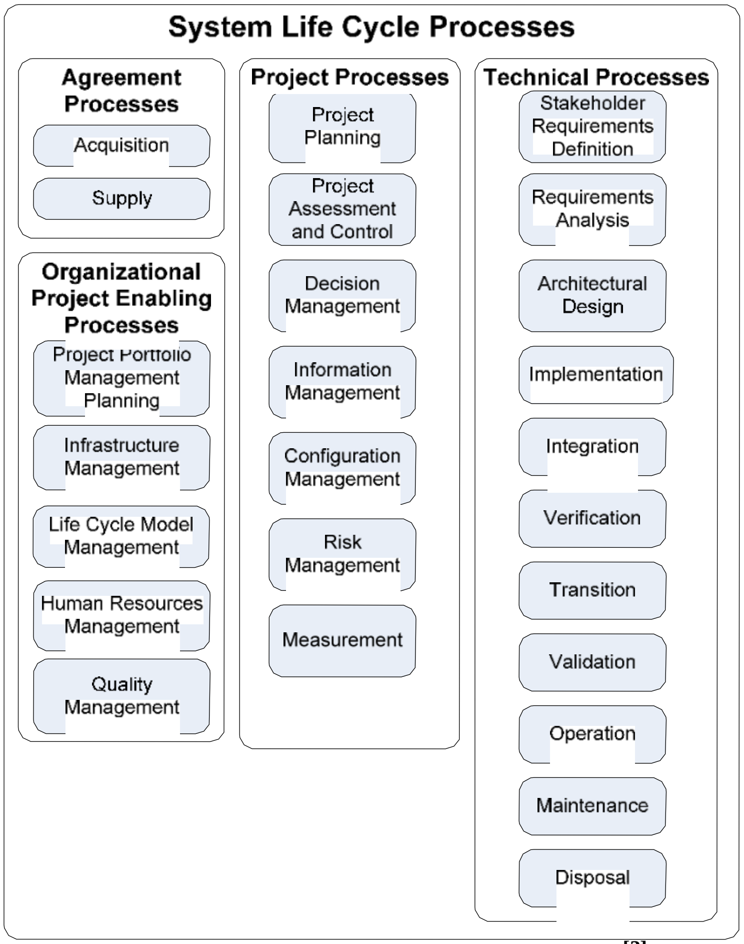

Figure 1 - Systems Lifecycle Processes [3]

Systems Engineering Management Plan (SEMP). For each project a SEMP is needed to govern how systems engineering will be performed. Most things may not change from project to project, but tailoring may be performed depending on the problem being solved and the customer wants and needs. The SEMP identifies the roles and responsibility interfaces of the technical effort and how those interfaces will be managed. The SEMP documents and communicates the technical approach, including the application of the common technical processes; resources to be used; and key technical tasks, activities and events along with their metrics and success criteria.

System Engineering Vee. A relational view of the systems engineering lifecycle in regards to verification and validation is presented in Figure 2. Requirements validation happens continually from the development of the concept of operations and architecture description to the component hardware and software specifications. It is critical to ensure that each lower level on the Vee is validated against the next higher level to ensure that course corrections are made as soon as possible to minimize the cost of changes in the system later. At various points throughout the process, gate reviews serve as a formal event to ensure the system development is on track with buy-in from the key stakeholders to include the customer. Entrance and exit criteria related to V&V activities are highlighted during these reviews. Further down the left portion of the Vee, design validation is performed as the system is further developed, ending with qualification hardware and software production. On the right portion of the Vee, verification activities are performed against the associated level from the left side of the Vee until the system is fully integrated. The Vee is completed when the production system factory acceptance test is executed against the concept of operations and the stakeholder requirements.

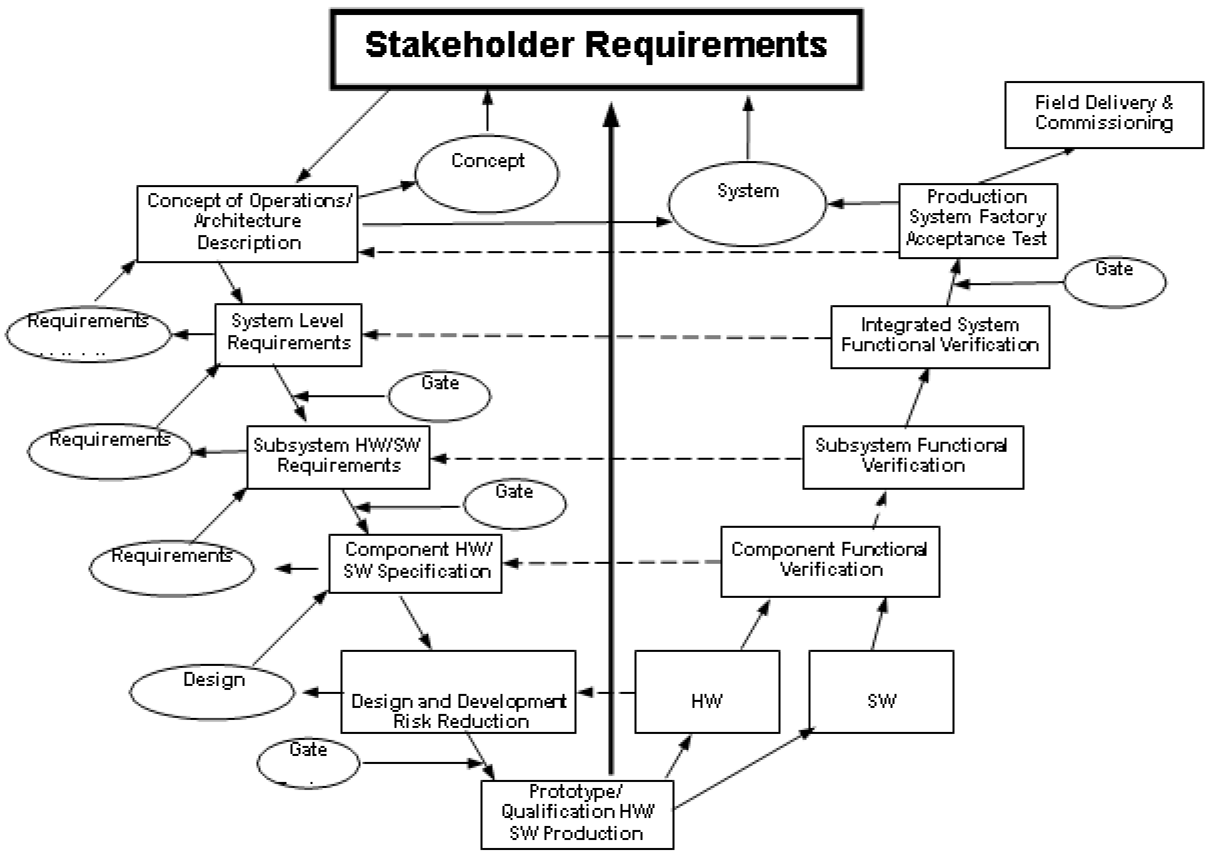

Figure 2 – Systems Engineering Vee

Concept of Operations. The Concept of Operations is a narrative description of the proposed solution, the problem it is intended to solve, and the details of its lifecycle from field commissioning through end-of-life disposal. It includes sufficient detail such that a Systems Architecture and the Systems Requirements can be derived and codified. Some of the critical considerations included in the Concept of Operations are:

- What problem(s) are we trying to solve?

- What are the proposed solutions?
- How will the system be used?
- What are the operational and non-operational environments?
- What are its operational and non-operational sequences and timelines?
- What is the system life expectancy?
- How will the system be maintained?
- What are the mandatory design attributes?

Systems Architecture. A top-level architecture of the system is matured over time as the system is developed. It contains a graphical/use case oriented overview of proposed technology solutions across the solution life time. Electrical, mechanical, structural, fluids, gases, control system and data interfaces, interactions, and co-dependencies are emphasized. The architecture is primarily driven by the Systems Requirements and Concept of Operations. Trade Studies, design analysis, and design synthesis are used to close on the final architecture of the system.

Requirements Documents. A baseline set of system requirements are developed to fit the stakeholder requirements, and the given concept of operations. System level requirements are decomposed into lower level requirements until the system is fully prescribed. They establish what has to be built, not how to build it. Requirements are validated to have the following attributes: they are complete, consistent, correct, verifiable, traceable, unambiguous and attainable.

System Vee Example. The development of the International Space Station was one of the greatest engineering projects in history. “The initial plans involved the direct participation of 16 nations, 88 launches and more than 160 spacewalks—more space activities than NASA had accomplished prior to the 1993 International Space Station decision. A significant leap in System Engineering execution was required to build and operate a multi-national space station. In a short period of time, NASA and its partners had to work out how to integrate culturally different system engineering approaches, designs, languages and operational perspectives on risk and safety.” [4] Similar to the Vee shown in Figure 2, the approached shown in Figure 3 was used during the development of the International Space Station.

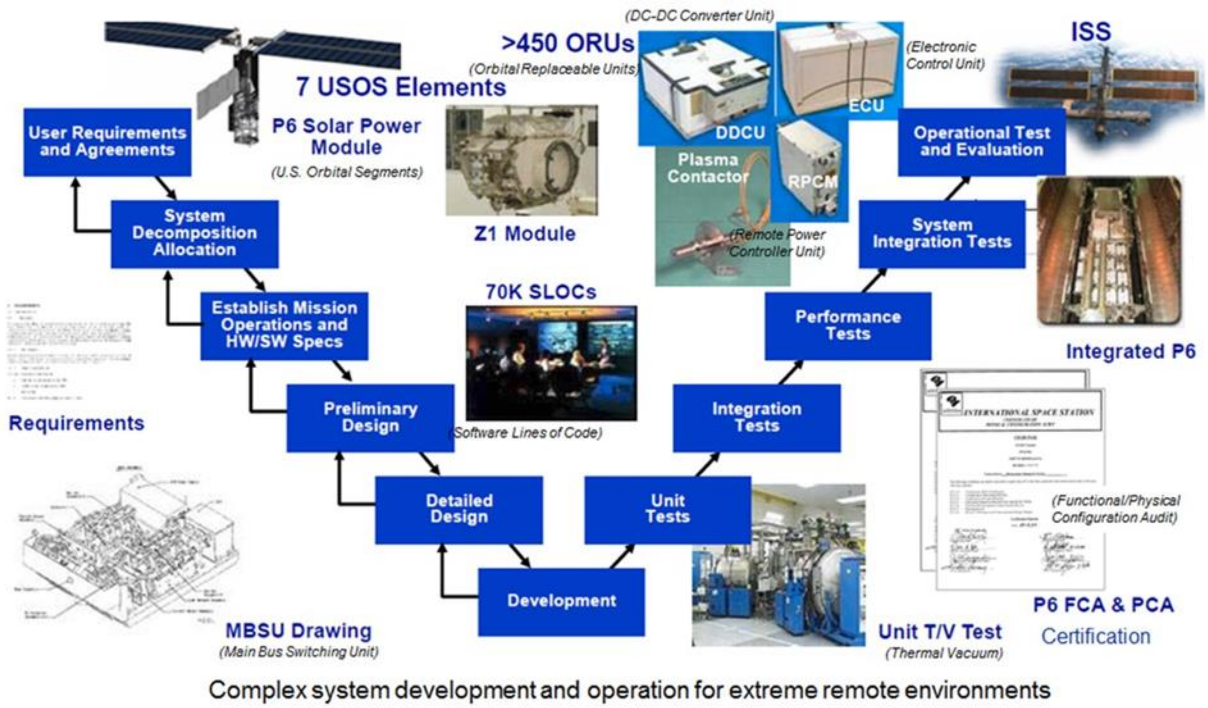

Figure 3, International Space Station, Applied Systems Engineering

Verification and Validation

Although verification and validation accomplish different goals they have a lot of the same components. Therefore, it's logical to present them together.

Verification and Validation Planning.
A verification and validation plan is created early in the development lifecycle and updated as requirements and designs are further developed. The plan captures the authority, approval and schedule to ensure that all the V&V activities will be accomplished. This plan also identifies the approaches, levels, methods and phases to be used when performed V&V. Those activities and associated recorded outcomes will be used to create V&V compliance reports in order to certify the system.

Verification and Validation Levels. As shown in Figure 2, systems are successively broken down into smaller and smaller systems and components until the system can be designed and implemented. V&V activities are driven by that same approach. Systems can be verified and validated at lower levels and then the higher levels can take credit for the work performed at the lower level. For example, a typical verification hierarchy from bottom to top for software control systems is unit test, software integration test, hardware/software integration test, hardware in the loop simulation test, hardware in the loop test, and system test. The trick is balancing risk, cost, and schedule to make sure that the sum of the verifications and validations lead to a validated system in the end. Generally as we move toward the top the cost of the tests increase and the variability of the available test inputs decrease.

Verification and Validation Methods. A predetermined method for performing V&V activities must be defined in the V&V plan. Methods vary from being subjective in nature, inspection, to very detailed and controlled, test. Things such as requirements criticality or customer emphasis should be considered when choosing a method. Requirements that correspond to the control of a hazard or a key performance measure of the system should be verified using the most stringent method possible. However, for simple yes/no decisions, Inspection is the least expensive way to verify requirements. For instance, did the caution light flash as required during a system fault? V&V methods are defined in Appendix A.

Verification and Validation Phases. V&V activities are performed using different methods at different levels at various phases of the development lifecycle. Generally, qualification tests will be performed on lower level systems and system components to verify detailed designs against requirements. System/stakeholder requirements are more often verified during certification and/or acceptance tests anchored to the qualification test results from the lower levels. Verification and validation phases are defined in Appendix B.

Verification and Validation Matrices. A verification matrix is used to trace each requirement to its associated verification activities to ensure their successful completion. The matrix is best supported by a requirements management tool. This matrix will include attributes such as verification levels, phases, methods, success criteria and results. Table 1 shows an example of a verification matrix. A similar matrix exists for validation activities, which are focused on systems and objectives in the concept of operations rather than requirements.

Table 1 – Sample Verification Matrix

ID	Paragraph	Requirement Text	Phase	Method	Level	Verification	Success	Results

SEMS Vs. Systems Engineering

Systems Engineering Supporting SEMS. As stated in CFR 250.1900, “the goal of your SEMS program is to promote safety and environmental protection by ensuring all personnel aboard a facility are complying with the policies and procedures identified in your SEMS program.” [5] In terms of safety, hazards are referenced many times throughout the regulation. Identification, elimination, and control of hazards are also keys to a strong systems engineering framework. Using systems engineering during the development of a new system or during operations of an existing system produces hardware, software, processes, training and documentation that can be operated safely and audited by SEMS programs. Therefore, systems engineering supports the common goal of SEMS.

Systems Engineering Framework and SEMS CFR Cross Reference. As an illustration of how systems engineering supports SEMS, Table 2 shows a matrix mapping the SEMS CFR to the sections of ISO/IEC 15288, Systems and software engineering – System life cycle processes that they enable. This standard is widely used in the systems engineering community and referenced by other well-known documents such as the International Council on Systems Engineering (INCOSE) Systems Engineering Handbook. It should be noted that the systems engineering framework contains many other processes that enable other activities and outcomes that are not part of the goal of SEMS, and are not shown in the cross reference. Likewise some of the sections of SEMS are prescriptive to areas that do not specifically fall under the systems engineering discipline, which are signified by the lack of associated mapping to the ISO standard in Table 2. By its nature systems engineering is not meant to account for every aspect of organizational processes, but this is not an indication that systems engineering does not enable those items as well.

Table 2 – Systems Engineering and SEMS Cross Reference

ISO/IEC 15288 Section	No.	30 CFR 250.1902 SEMS
6.4.1	1	General (see § 250.1909)
6.4.3	2	Safety & Environmental Information (see §
6.4.1	3	Hazards Analysis (see § 250.1911)
6.3.5	4	Management of change (see § 250.1912)
6.4.9	5	Operating procedures (see § 250.1913)
6.4.9	6	Safe work practices (see § 250.1914)

6.4.9	7	Training (see § 250.1915)
Many sections support this item	8	Mechanical Integrity (Assurance of Quality & Mechanical Integrity of Critical equipments) (see
6.4.7	9	Pre-Startup review (see § 250.1917)
No direct alignment	10	Emergency response and control (see § 250.1918)
No direct alignment	11	Investigation of Incidents (see § 250.1919)
No direct alignment	12	Auditing (Audit of Safety and Environmental Management Program Elements) (see § 250.1920)
6.3.5	13	Record keeping (Records & Documentation) (see § 250.1928)
No direct alignment	14	Stop Work Authority (SWA) (see § 250.1930)
No direct alignment	15	Ultimate Work Authority (UWA) (see § 250.1931)
No direct alignment	16	Employee Participation Plan (EPP) (see §
No direct alignment	17	Reporting Unsafe Working Conditions (see §
No direct alignment	a)	You must include a job safety analysis (JSA) for OCS activities identified or discussed in your SEMS program (see § 250.1911)
No direct alignment	b)	Your SEMS program must meet or exceed the standards of safety and environmental protection of API RP 75 (as incorporated by reference in §

Case Study - Validation

A critical consideration supported by verification and validation is ensuring that the appropriate level of controls have been developed at each level of the system to satisfy the top level system hazards. In fact, much of the requirements, design, and code for critical control systems exist to satisfy this need. This case study illustrates a potentially hazardous situation that existed in a fielded system and proposes a process to show how it could have been identified and addressed during system development.

The Problem. During a control system code review, it was discovered that subsequent to particular failure modes the backup controller would not take control in the event of a failure in the primary controller. It is illustrated later in this case study how this capability is critical to address a loss of containment hazard.

The Analysis. The issue was related to the backup controller monitoring a file containing a status bit indicating the health of the primary controller. As intended, if the primary controller posted a failed status, the backup controller would assume control. However, if the controller failure mode resulted in an inability to update the file with a “failed” status, the backup would not assume control of the system, leaving the system without an active controller.

Temporary Solution. An additional sequence counter complimentary to the status bit would have eliminated this situation. The backup could assume control if either the status bit was failed or the sequence count failed to increment.

It was further noted that requirements specifications were not created during the system development, preventing V&V activities to be properly performed.

Addressing the Root Cause. An example of how a system level hazard can successfully be addressed by the software given an integrated V&V approach with supporting hazard analysis, failure mode effects analysis, and requirements traceability is illustrated in the following sections. It should be noted that only a very small portion of the analysis, concepts, attributes, and data is shown for brevity. Each of these supporting elements requires their own forum to fully demonstrate.

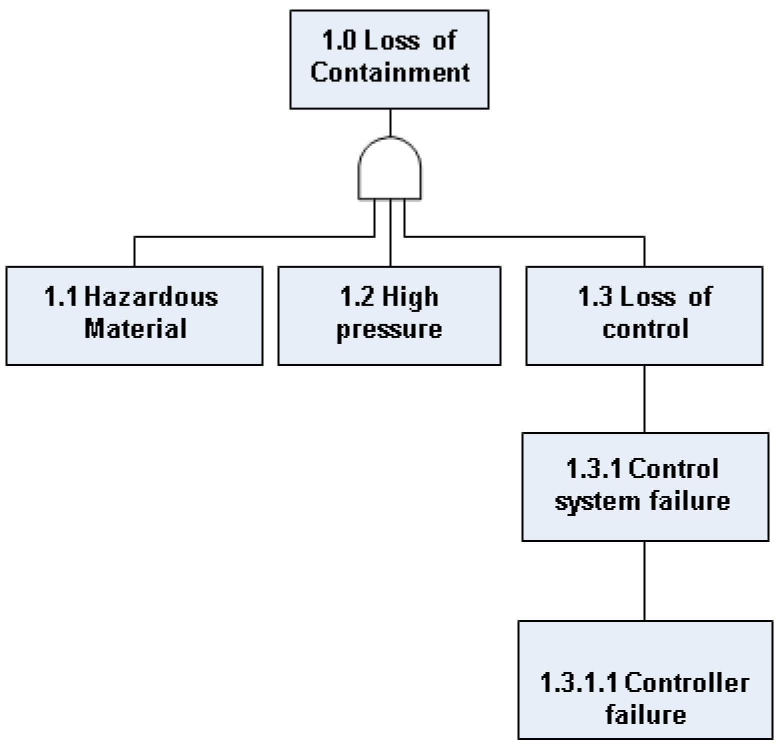

Figure 4 – System Fault Tree

Hazard Analysis. In order to reduce the risk of a major system failure hazards must be identified. Several tools are used to identify the possible hazards associated with a system's operation. One such tool is the Fault Tree shown in Figure 4. Note that this example is generic, but could apply to any hazardous situation in any system at any level. At the top is the loss of containment. In this example, three things are necessary for that event to occur; hazardous material, high pressure and loss of control. While each of these items has many other causes, the diagram focuses on a control system failure, caused by a controller failure. Again, this failure may be broken down further, but let's stop there for this example and transition to a control to mitigate that hazard, such as a redundant controller. A control to prevent this hazard from leading to a loss of control is prescribed by requirement req1.

***req1**: The control system shall provide continued operations with no degradation in control in the event of at least one control system failure.*

This requirement should be validated against the Concept of Operations to ensure that it meets the program objectives, problems to be solved, stakeholder requirements, and lifecycle considerations of the system. Once validated the requirement may drive a need for a redundant set of electronics within the system architecture description, Figure 5.

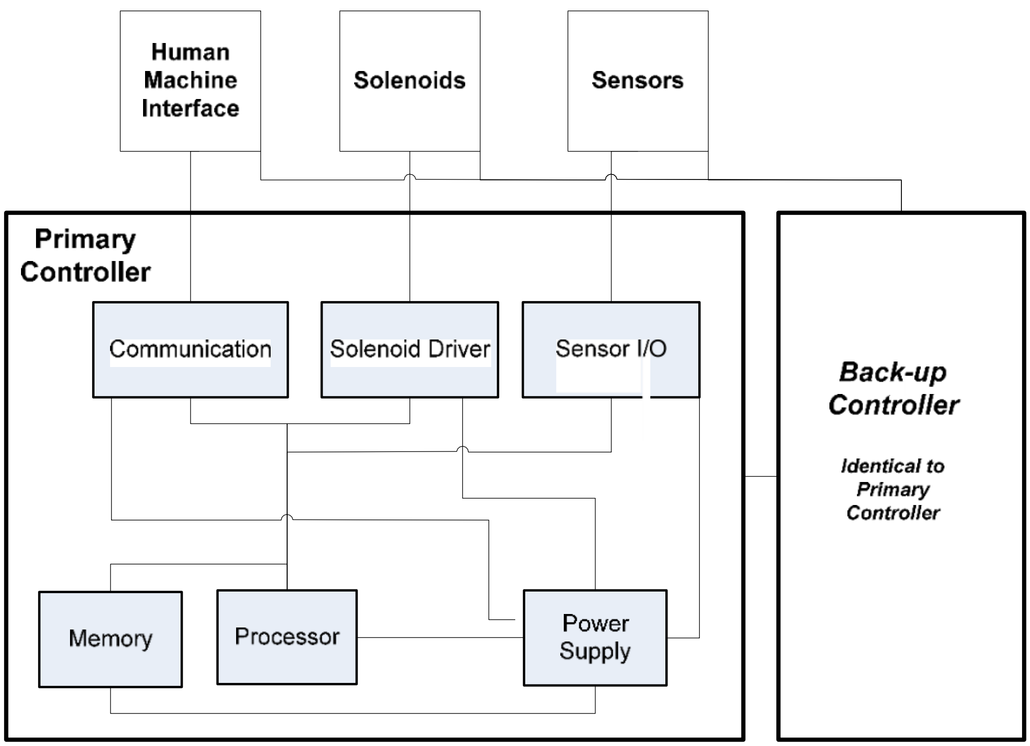

Figure 5 – Control System Architecture Diagram

Requirements Decomposition. In order to ensure that the system level requirements are fully implemented, they must be decomposed into lower level requirements and validated at each level to ensure that the final system will properly address the hazards and meet the customer expectations. The following two requirements are decomposed to the controller level from req1 to further stipulate how the system will address the need for continued operations without degradation in the event of a failure.

req2*: The Controller shall provide a mechanism for detecting any of its own failures.*

req3*: In the event of an in-control controller fault, the Controller shall switch from the Primary to the Back-up when operating in dual mode.*

Figure 6 shows how the requirements in this case study are decomposed from the Control System down to the Controller Software.

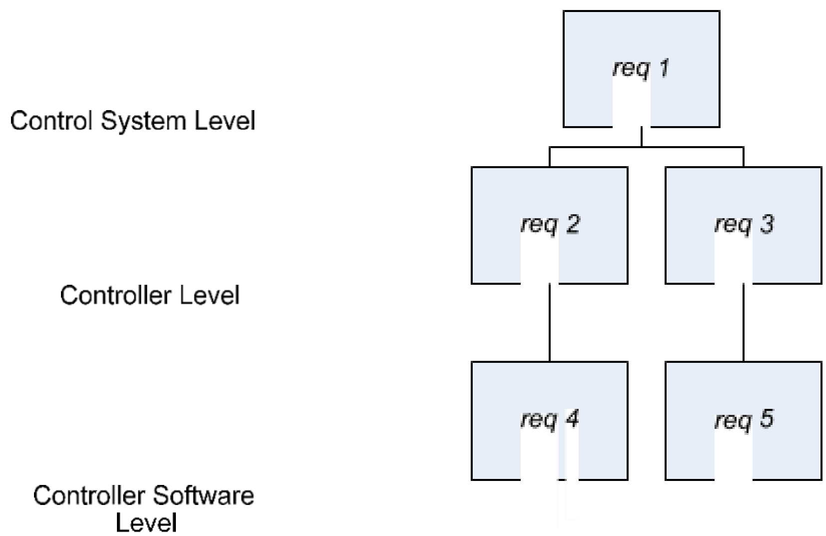

Figure 6 – Requirements Tree

Hazard Analysis Interrelationship with the Failure Modes and Effect Analysis. The Hazard Analysis and Failure Modes and Effects Analysis (FMEA) are complementary analyses that by themselves have unique advantages and limitations, but together provide a comprehensive means to identify, understand, and eliminate or control the risks present in the system design. Proper coordination between these analyses is important to reduce duplication and ensure their maximum effectiveness. The FMEA provides data to support the hazard analysis in the assessment of compliance with failure tolerance requirements and assures the control and verification of hazard causes. Figure 7 illustrates the relationship between hazard analysis and FMEA.

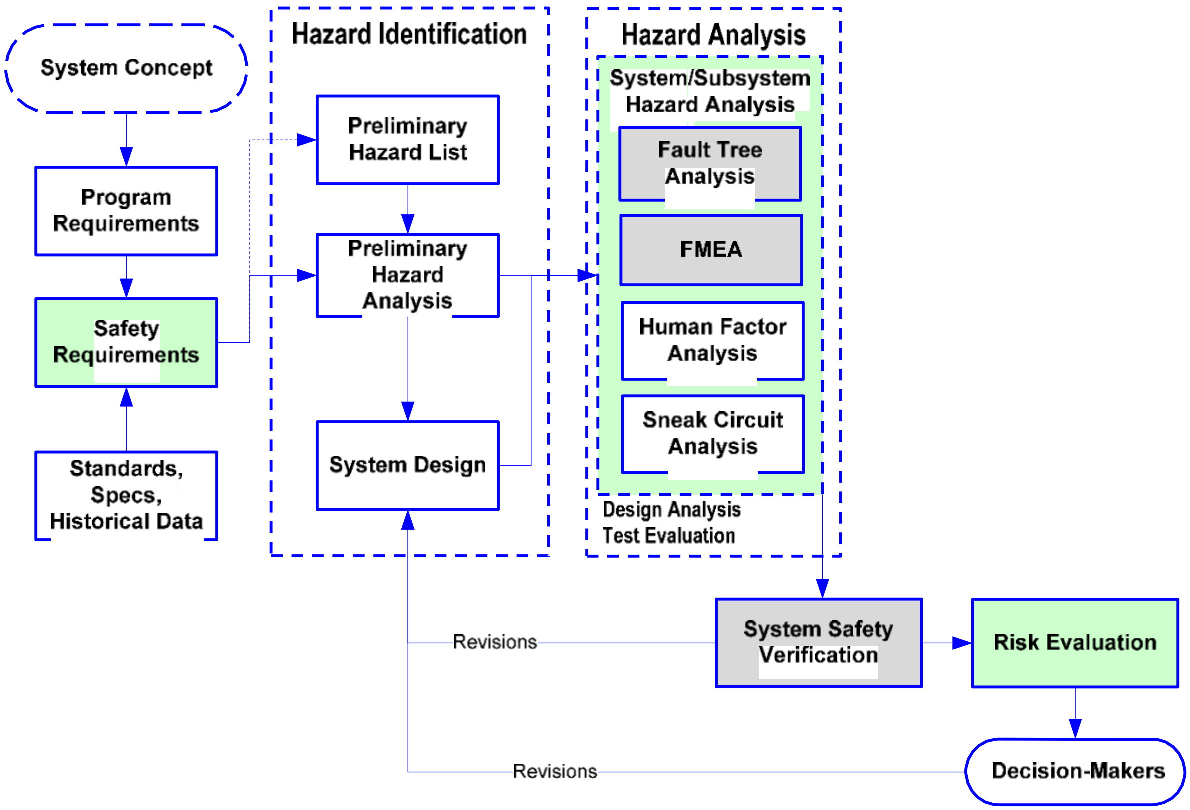

Figure 7 – Hazard Analysis and FMEA Interactions

Failure Modes and Effects Analysis (FMEAs). Failure Modes and Effect Analysis should be performed throughout the design stage of the systems development lifecycle to identify the potential failures and effects of those failures given the current design with the goal of designing out critical failure modes and increasing reliability. Results of the FMEA are used to validate that the current requirements meet the system reliability needs of the customer as well as to verify that the current design meets those requirements. Figure 8 shows a portion of a FMEA and detection mechanism centered on a potential failure mode of the controller hardware related to control of the loss of containment hazard. It should be noted that FMEAs are primarily performed on design areas with the highest criticality; hazards being one of them.

Item Description	Potential Failure Modes	Causes	Effects	Detectability	Control
Controller	Loss of external control	Processor Halt	Loss of external communication	Fails to communicate with backup control system	Heartbeat verified by cross-channel controller

Figure 8 – FMEA Matrix

FMEA results drive software requirements. For complex control systems, software will need to be used to determine when to switch and subsequently handle switching to a redundant controller. Given *req2* and *req3* and the results of the FMEA in Figure 8, the following software requirements address the mechanism in which this control is executed:

req4: *The software shall monitor the health of the cross channel Controller every cycle.*

req5: *The Back-up Controller shall disqualify the Primary Controller if the Primary Controller status counter indicates stale data for two consecutive cycles.*

Conclusion. Examining the series of steps above shows that there are many tools and processes that are used to thoroughly validate requirements associated with hazards and failure modes of the system. Without full traceability throughout the system there are higher potentials for hazards to not fully be addressed in the fielded system.

Case Study - Software Verification

In the previous case study we focused on validating the requirements to ensure the system that was built was the right system in regards to addressing system hazards. Those validation activities serve the purpose of setting the stage for what the system needs to be designed to. The next step is verifying the design meets the requirements.

We can use the requirements from the validation case study to show how these activities can be planned and executed. Consider Table 3 to illustrate a sample of the verification matrix to show how the critical software requirements could be verified. Note that in this view only the software requirements are covered for brevity. Hardware verification activities and verification activities at higher levels of the system are performed in a similar manner, but use slightly different methods and verification approaches, such as build-to design documents. To close out the verification activities, all requirements must pass verification or have an approved deviation from the requirements.

Table 3 – Detailed Verification Matrix

ID	Requirement Text	Phase	Method	Level	Verification Requirement	Success Criteria
req4	The software shall monitor the health of the cross channel Controller every cycle.	Qualification	Test	Hardware /Software, Integrated (HW/SW, Int)	With the Primary Controller in control while in dual mode, monitor the reading/ writing of each controller status from the cross channel	Show that both Primary and Backup Controllers read cross channel Status every major cycle in between write cycles to the cross channel status bit and cycle count (i.e. show there are not multiple writes to counter in between each read)

req5	The Back-up Controller shall disqualify the Primary Controller if the Primary Controller status counter indicates stale data for two consecutive cycles.	Qualification	Test	Hardware /Software, Integrated (HW/SW, Int)	With Primary Controller in control while in dual mode, modify status counter file to show: 1) stale data after the Primary Controller updates counter and before back-up reads file for two consecutive cycles. 2) stale data every other cycle.	Show Primary Controller status is 1) set to disqualified, 2) does not get set to disqualified

Verification Requirements. Several scenarios are listed in the verification requirements fields of Table 3. This will be the case in most instances with the list being much greater than what is shown here. The verification requirements explain how to verify the design meets the requirements text. The operational nature and environment in which the system will operate must be considered when developing verification requirements. Remember that requirements are not written to explain how a system should be built, just what it needs to conform to so verification requirements are critical to provide verification details.

The verification requirements in Table 3 mentioned the use of a file that stores a status counter. The software was designed to use a shared file between controllers to pass along status information. It’s important to note that this design aspect accommodates the requirements, but there are many other design options which could also be chosen. Again, the FMEA evaluates the failure modes and risk of not controlling a hazard given this design.

It’s important to not only add tests to verify that the design works per the requirements, but to also add some off nominal tests to really flesh out the design. For req5, test two does exactly that. Given the potential asynchronous nature between the controllers in regards to the status file update, this test is added to catch the anomalous instance in which the backup reads the counter twice between write cycles from the primary.

Success Criteria. The success criteria clearly define the expected results when executing the verification requirements. What do I need to show to take credit for the verification of that requirement? This is done to ensure that the correct test objective is met. Without this clear guidance the wrong outcome could be verified or objectives outside what is necessary may be verified which can add significant extra effort to the test effort.

Conclusion

Systems Engineering. Formal systems engineering processes have been heavily used for decades in industries such as aerospace to develop highly critical complex systems with first time success. Its interdisciplinary full lifecycle approach leads to systems that are more efficient, reliable and safe. With offshore drilling and operations becoming increasingly complex, the Oil and Gas industry could greatly benefit from the application of systems engineering when designing new or upgrading existing systems.

Systems Engineering Supports SEMS. A SEMS program is limited by the maximum capability of the systems they audit in preventing unsafe operations and increasing environmental protection. The systems engineering framework also provide focus to the identification and elimination and/or control of hazards. A strong system engineering process can greatly increase a systems capability to act as an enabler to a rigorous SEMS program.

Verification and Validation of Hazards Controls at all Levels is Critical. Proper verification and validation of system design and requirements can be complicated, but there are systems engineering methods, activities, and tools to help. Using these methods provides the best opportunity to manage stakeholder requirements such as systems that are safe to operate. The systems engineering Vee provides a rigorous approach to validate at each level that the right system is built and to verify that the system is built the right way. Verification and validation is critical developing a system that meets customer expectations.

References

[1] This adapted excerpt is taken from ISO/IEC 15288:2008, section 5.3.2.4 on page 13, with the permission of ANSI on behalf of ISO. © ISO 2013 – All rights reserved.

[2] This adapted excerpt is taken from ISO/IEC 15288:2008, section 5.3.2.5 on page 13, with the permission of ANSI on behalf of ISO. © ISO 2013 – All rights reserved.

[3] This adapted excerpt is taken from ISO/IEC 15288:2008, Figure 4 on page 12, with the permission of ANSI on behalf of ISO. © ISO 2013 – All rights reserved.

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[5] CFR 250.1900 Subpart S—Safety and Environmental Management Systems (SEMS) [6] NASA/SP-2007-6105 Rev1, NASA Systems Engineering Handbook

Appendix A – Verification and Validation Methods

Inspection: The visual examination of a realized end product, inspection is generally used to verify physical design features or specific manufacturer identification. [6]

Analysis: The use of mathematical modeling and analytical techniques to predict the suitability of a design to stakeholder expectations based on calculated data or data derived from lower system structure end product verifications or validations. Analysis is generally used when a prototype, engineering model or fabricated, assembled and integrated product is not available. [6]

Demonstration (Verification): Showing that the use of an end product achieves the individual specified requirement. It is generally a basic confirmation of performance capability, differentiated from testing by the lack of detailed data gathering. Demonstrations may involve the use of physical models or mockups. For example, a requirement that all controls shall be reachable by the pilot could be verified by having a pilot perform flight-related tasks in a cockpit mockup or simulator. [6]

Demonstration (Validation): The use of a realized end product to show that a set of stakeholder expectations can be achieved. It is generally used for basic confirmation of performance capability and is differentiated from testing by the lack of detailed data gathering. [6]

Test (T): The use of an end product to obtain detailed data needed to verify performance, or provide sufficient information to verify performance through further analysis. Testing can be conducted on final end products, breadboards, brass boards or prototypes. Testing produces data at discrete points for each specified requirement under controlled conditions and is the most resource-intensive verification technique. [6]

Appendix B – Verification and Validation Phases

Qualification: The process of assuring that a product, when built in accordance with the design, shall perform as specified, within applicable margins, during and following exposure to specified induced environments, including self-induced environments, encountered during mission operation, such as salt spray, humidity, temperature and pressure.

Certification: A process that includes satisfactory completion of a predefined set of tests and inspections on a product of the final design configuration for the purpose of demonstrating the operational envelope of a configured item.

Acceptance: The process that demonstrates that each delivered Configuration Item has acceptable functionality and performance, has been manufactured as designed, is free of manufacturing and workmanship defects, and provides evidence of overall product acceptability for delivery to the customer.

Operational: Operational Tests are equivalent to Sea Trials Testing.

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