Pacific Northwest NATIONAL LABORATORY

PNNL-39050

Grid Architecture Mapping to Understand Transformation (GAMUT)

Methods and Framework Architecture

February 2026

Artis Riepnieks
Eric G. Stephan
Priya T. Mana
Jaime T. Kolln
Paul K. Wetherbee
Jeff E Dagle

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights**. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062
www.osti.gov
ph: (865) 576-8401
fox: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: http://www.ntis.gov

PNNL-39050

Grid Architecture Mapping to Understand Transformation (GAMUT)

Methods and Framework Architecture

February 2026

Artis Riepnieks
Eric G. Stephan
Priya T. Mana
Jaime T. Kolln
Paul K. Wetherbee
Jeff E Dagle

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

Grid architecture (GA) was developed to address the need for a comprehensive view of power grid challenges and solutions. GA can be viewed as a relatively consistent and fixed high-level approach; however, for any instantiation of grid structures, a combinatorial explosion results from each detailed lower-level expansion. This constitutes the main challenge with GA—it is a grid architect's view of the system, which can be difficult to translate into specific implementation solutions. Grid Architecture Mapping to Understand Transformation (GAMUT project) seeks to bridge that gap by integrating subject matter expertise across GA structures, providing users who lack expertise in GA approaches with valuable insights and informational materials.

GAMUT initially seeks to answer feasibility questions to the application of GA based tools, in particular supporting demonstrations of technologies nearing commercial deployment. System-level expectations are that a GA baseline needs to be established within the GAMUT Tool in order for GA to be the common framework to which any technology-specific approach is tied. This report explores a potential information ingestion and documentation framework that a GAMUT software tool would provide. The main concepts that enable the solution domain of GAMUT are discussed, and examples are provided.

The solution domain leverages already-existing technology and concepts related to GA, knowledge management, and other relevant areas. To assess GAMUT building blocks and the overall approach, a feasibility assessment will follow the framework and methodology discussed in this document, which is rooted in systems engineering and GA architecture concepts.

Contents

Figures

1.0 Introduction

This document establishes the approach of applying grid architecture (GA[1]) as an evaluation mechanism for understanding grid transformation. The approach involves decomposing demonstration project topics and related information (including documentation) which is necessary to map technology and implementation projects onto the GA. An assessment method is then presented for evaluating and describing the outcomes of the information mapping to GA structures for enhanced decision-making. This process will then be evaluated through a systematic feasibility assessment for the GAMUT project to discern the practicality, value, and potential barriers for developing a tool (the GAMUT Tool) that satisfies the requirements of the project.[2] A feasibility assessment will follow this document, providing actionable information on projected success, risks, costs, and value for strategic (project-level) decision-making. This document is organized into four parts:

- **Baselining GA**. GA is a process that is based on systems engineering principles combined with theory of networks which is specifically applied to the electrical grid. It is traditionally a conceptual process with a high level of abstraction; it is well defined as an approach but not as a model. Section 2.0 establishes a baseline approach for a GA model for GAMUT project purposes and provides insights into potential challenges and opportunities.

- **Solution documentation framework**. Within the GAMUT paradigm, the value of understanding technology demonstration projects and the "big-picture" of integrations comes from mapping to GA. This mapping organizes a lot of information from various sources that will be gathered and collated. Therefore, the establishment of a documentation framework is necessary as a starting point for interactions with GAMUT.

- **Define assessment method**. During the mapping and iterative discovery processes across the GAMUT Tool instantiation, guidelines and a common methodology are established to facilitate consistent comparisons between methodology outcomes. The assessment method involves evaluation of a criteria data model for more quantitative assessment approaches.

- **Develop a solution documentation framework and a baseline for GA**. This task consists of developing a common method for documenting and categorizing technology solutions and establishing traceability to overall grid objectives and a baseline for GA that enables mapping to GA concepts and organization by GA structure. This draws upon the qualities and properties being mapped from GA but extends them to a lot more detailed levels (lower in level of abstraction) of design and implementation to provide a repeatable, machine-readable method of organizing the data. The outcome of this task is to describe the documentation framework, data model, and mapping approach.

[1] JD Taft, R. Melton. "Grid Architect's Guidebook: Second Edition", 2020, Richland, PNNL

[2] See the "GAMUT Concept Document."

2.0 Grid Architecture and Industry Structures

System architecture provides a conceptual framework that outlines the structure, behavior, and key constraints of a system. It aims to help build an understanding of the system's overall configuration and attributes and the interactions among its components. System architecture is typically documented and specified in a formal manner. The discipline of systems engineering includes core principles and methodologies that are part of the GA development process.

GA,[1] developed under prior Department of Energy (DOE) projects, is the application of system architecture principles, network theory, and control theory to the electric power grid. It represents a high-level description of the entire power system, spanning multiple interdependent networks of structures and serving as a crucial tool to comprehend and define complex interactions. GA provides methods to document and specify the grid's architecture at the highest and broadest level, allowing for systematic analysis of the complex interactions across the grid and the GA structures, both in its current state and as it evolves into the future. These interactions include the electrical infrastructure itself, supporting infrastructures, and other financial, jurisdictional, and regulatory dependencies.

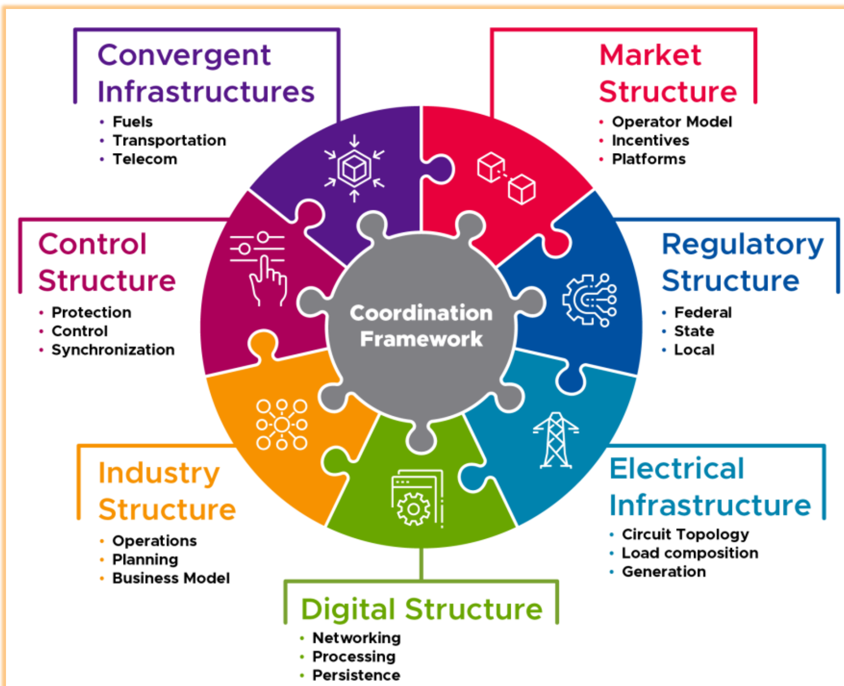

Figure 1. Grid architecture network of structures.[2]

The GA top-down high-level structure approach (depicted in Figure 1) provides a foundation for analyzing broad grid challenges as well as documenting and specifying architectural structural requirements to guide grid transformation strategy and planning. Identifying dependencies between structures enables informed design decision-making that reduces barriers to adoption and the broad deployment of new technologies. The architecture establishes the bounds for

[1] https://gridarchitecture.pnnl.gov.

[2] Pal, Seemita, and Wollman, David, "A Practical Introduction to Common Grid Architecture Techniques" (2024), https://doi.org/10.2172/2342144.

specific solution designs, and it has been utilized to inform policymakers as well as other DOE research and development projects. However, no similar methodology has been established to evaluate how specific technology solutions fit into an ultra-complex system-of-systems ecosystem. Furthermore, there are no universal tools for easily linking technology solutions to GA structures that would be suitable for broad application by DOE, researchers, industry, and other stakeholders. This project seeks to address this gap through the structured collection of information, identification and characterization of technology solutions, and development of knowledge management frameworks that can be applied to software-based GA solutions, recommendations, and queries. The outcome is expected to provide architectural insight for technically specific contexts—for example, providing regulatory structure insights for electrical infrastructure deployment challenges.

2.1 Project Overview

The project aims to establish an approach for systematically documenting and understanding the operating context, specifications, processes, benefits, regulations, and impacts of various technologies and solutions to support grid modernization while establishing the feasibility of such an approach. Fundamental GA concepts are systematically applied to analyze and understand the various components, interdependent systems, and interactions of new technology—including hardware, software, and processes—being deployed in the electric system. This approach also enables stakeholders to measure the effectiveness of different technology deployment scenarios for the future grid and how these solutions can be more easily scaled and implemented across jurisdictions. A framework for systematic application of GA techniques and structural assessments will support the collection and organization of information and provide insights into requirements, dependencies, and capabilities.

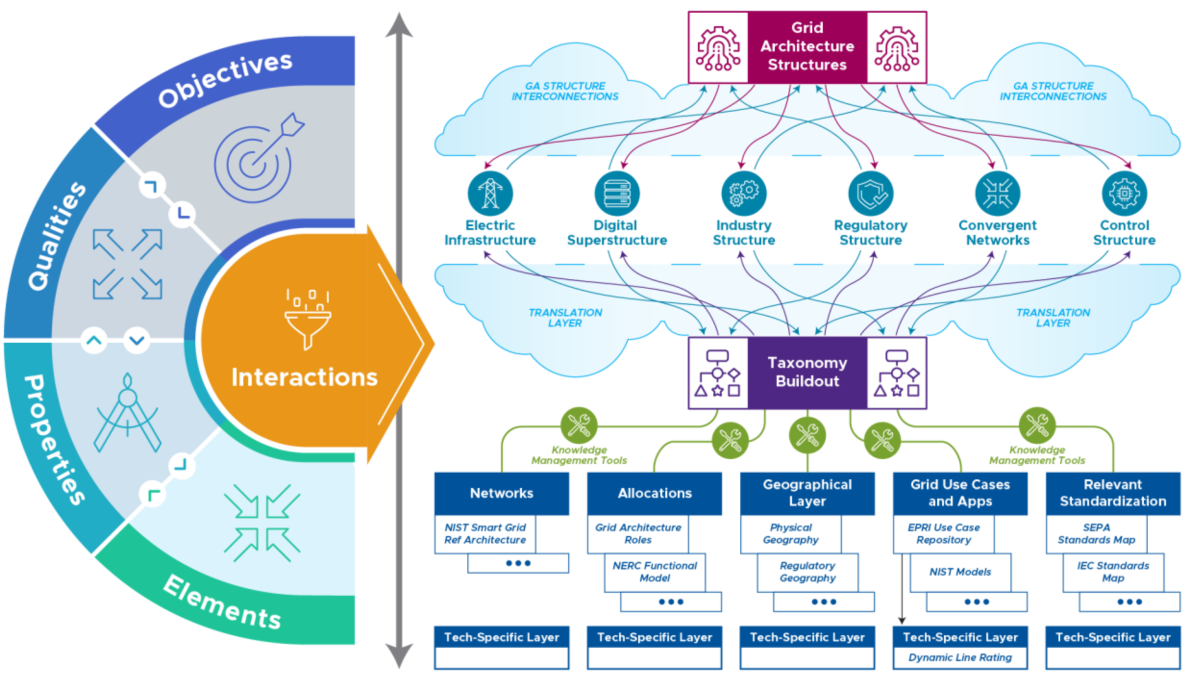

Figure 2. GAMUT conceptual architecture for architecture knowledge management.

In order to assess feasibility, the team needs to select and analyze concepts of a potential solution. Figure 2 shows the GAMUT Tool conceptual diagram. The left side of the diagram depicts the GA approach—including system objectives, qualities, properties, and elements—along with input options and potential routes for traversing in-between. For example, a user who only has specific technology-level objectives can still interact with the GAMUT Tool, even if they lack knowledge on the full set of grid objectives. The same is true for system qualities, whether they are known or need to be estimated and validated. When validation is necessary, it can be carried out through the use of GA methods. Adopted methods within GAMUT are discussed in Section 2.2.2, and system properties and elements are mapped to the desired qualities or objectives to establish a more holistic approach. The interaction linkages are applicable to any abstraction level (from most abstract GA views to detailed technology perspectives) within the GAMUT Tool approach, as depicted on the right side of Figure 2.

GA as a holistic approach is typically applied at a high abstraction level. The chosen decomposition approach is to use GA structures to establish more specific aspects of the power grid while maintaining a holistic approach (a baseline for instantiation of GAMUT approach, based in GA). The structure interconnections, which are discussed in Section 2.2, provide traceable linkages that allow information to be pulled from any of the structures. Below the structures layer, each of the structures must get decomposed and abstracted through data structures/classification (taxonomies) and shared meaning (ontology) which GA can help with. Decomposition and the establishment of a data classification (taxonomy buildout) connect the GA structures to the main knowledge repository. Given the GAMUT Tool requirements, the knowledge management approach and the database itself must provide as comprehensive coverage as possible with many crosscutting viewpoints. For example, while the geographical pillar knowledge type is specific in nature (and requires specific software tools), it is exhaustive (i.e., it covers the entire state, country, world) and provides a crosscutting view for assigning regulatory structure (state regulations), industry structure (entity responsibility footprints), and electric infrastructure knowledge elements. Existing databases can be leveraged within a specific domain and linked through the GA data structures and associations.

For example, GAMUT Tool users would interact at the technology specific domain level without any previous experience or knowledge of GA and its terminology. Queries can be prepared in the background, and information can be prepared for presentation at the technology specific level. Looking at a specific technology (e.g., dynamic line rating [DLR]) it is mapped (associated) to a specific use case(s) based on existing knowledge bases of various frameworks (e.g., Electric Power Research Institute [EPRI] Use Case Repository or National Institute of Standards and Technology [NIST] defined use cases). Figure 2 “Grid Use Cases and Apps” (the use case knowledge base) are mapped through the “taxonomy buildout” to the higher abstraction level of GA structures. From the GA structure interconnections layer shown in Figure 2, dependencies can be traced between other structures, allowing deep dives back into data/information knowledge base. In the example of DLR, the use case can be mapped to at least electric infrastructure, digital superstructure, and control structures. Looking at the DLR context in the control structure can lead to the “Allocations” knowledge base, where context-specific information can be further associated.

Another way to walk through the conceptual approach is to consider an example of a cybersecurity query. The DLR technology specific use cases are queried within “Grid Use Cases and Apps” (from Figure 2) knowledge repository to associate cybersecurity aspects of the technology. Identified grid use cases can provide data classification structure (taxonomy) linkage to GA structures. A search through cybersecurity aspects can reveal the dependency to “digital structure” and “regulatory structure”. A downward linkage to requirements and the relevant standardization knowledge base can reveal relevant cybersecurity standards/requirements/lessons-learned. Additionally, cross-checks can be performed to evaluate whether technology and project elements and properties correspond to other cybersecurity related requirements and data/information/knowledge in the GAMUT Tool.

2.2 Grid Architecture Baseline

GA is a top-down approach that is broad and generic enough to include and support all entities and all activities taking place in the grid domain, which is an ultra-large-scale, complex, and dynamic system. Because of the GAMUT Tool's requirements and assumptions (Figure 2), users must address domain-specific challenges and questions. This illustrates the biggest challenge for GAMUT Tool—how to bridge the gap between the potential user (working bottom-up from a technology deployment viewpoint) and a grid architect (working top-down) while maintaining traceability and allowing for cross-domain knowledge exchange.

> **GA baseline** is a process for choosing the right context and abstraction level to enable technology- specific information mapping onto the larger context of GA structures and inter-structures. **This process is essential to building GAMUT Tool as well as to its operation**

This section describes the process of GA baseline and sufficiently decomposing the GA approach to allow reverse engineering of GA approaches (the user's bottom-up approach). Essentially, the GA process is applicable for users who's detailed, domain and context-specific information can be mapped to large GA structures without loss of traceability or contextual information. From a GA perspective, this means specifying increasingly more detailed levels of information to create interface points between the user and the hypothetical architect.

Because GA is a top-down approach, tool development begins with GA baselining and understanding the GA methodologies so that they can later be reverse-engineered from individual bottom-up instantiations.

2.2.1 Grid Architecture Structures

Because the GA approach forms the core of GAMUT Tool design, it must be compatible with GA and systems engineering principles. In a top-down view, the GA process looks at six structures[1], with the coordination framework at the center (Figure 1). Each of these structures represents a unique part of the GA and has its own unique structure within. Without diving into the components of each structure, we establish that these structures are interconnected and related to each other via specific interfaces. An entity relationship diagram of how top-level GA structures interface with each other is depicted in Figure 3[2] (JD Taft, 2020).

[1] Recently it was determined that a market structure needed to be added to compliment the industry structure rather than as part of it, since these are typically insulated from each other in practice.
[2] JD Taft, R. Melton. "Grid Architect's Guidebook: Second Edition", 2020, Richland, PNNL

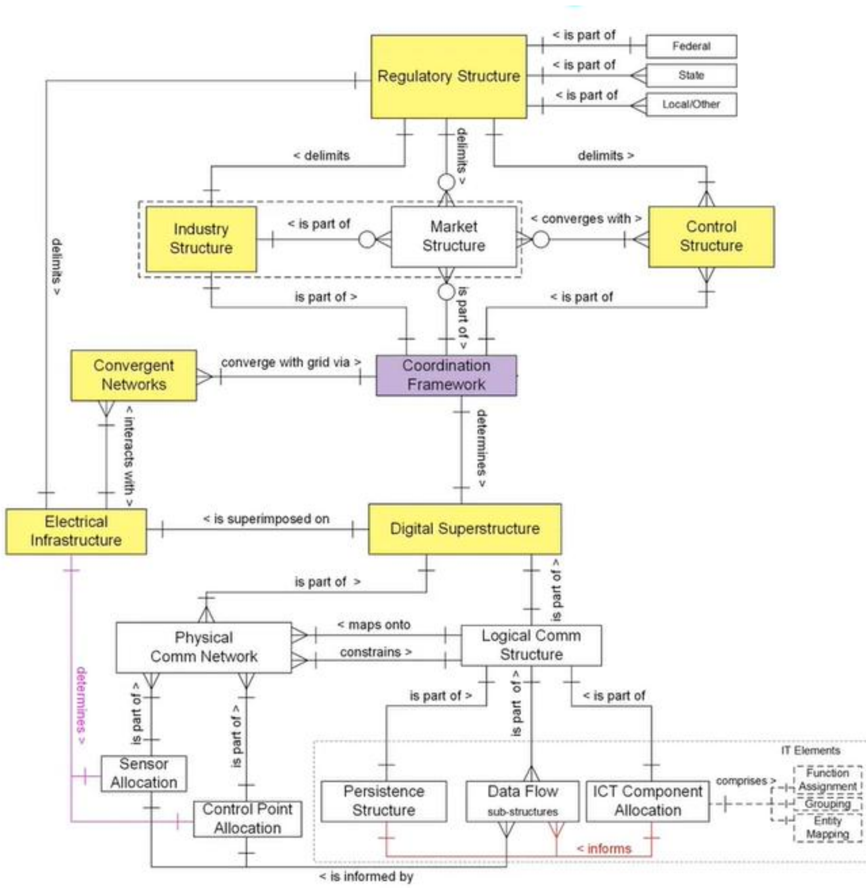

Figure 3. Grid architecture network structure dependencies.

From the GAMUT Tool and GA baselining perspective, the dependencies can be traced between structures, ensuring a systemic approach.

Each structure captures an integral part of the overall GA (JD Taft, 2020):

- **Electrical structure**. This structure primarily focuses on circuit topology and various types of energy resources and connection types. Considerations can include load composition, generation structure, and the locational value of emerging assets. At high abstraction levels, it can be represented as a one-line diagram of circuit topology, and at lower levels, it can include actual device types and electric properties.
- **Industry structure**. This structure represents how organizations relate to each other in an industry segment. It covers multiple views, including operations, planning, and markets. Markets (where they exist) are strongly connected to grid control and coordination because they drive optimization goals. A representation of industry structure shows how all the entity classes (architectural elements) are related. A change in one area can affect the other areas.
- **Market structure**. In the GA context, market structure concerns the products and services (e.g., energy and ancillary services) bought and sold by various entities. It focuses on identifying the market's products and their value, the operators of the markets, the participants in the markets (entities represented as architectural elements), and how they are connected (relationships between the elements).

- **Regulatory structure**. This structure identifies which entities perform regulation, which entities are regulated, and what aspects are regulated. The structures identified through the GA process focus on jurisdictions, boundaries, and scope. The regulatory structure has inherent hierarchies, such as federal, state, and local/municipal structures. For example, federal regulation structure, mostly for bulk systems, involves oversight by U.S. government agencies, including the following:
    - Federal Energy Regulatory Commission
    - North American Electric Reliability Corporation
    - U.S. Environmental Protection Agency
    - Internal Revenue Service
    - U.S. Department of Agriculture
- **Digital structure**. Having undergone several trends, this structure will continue to undergo rapid changes due to grid modernization efforts. This nonlinear advancement reshapes the convergence of information and communications technology with the grid, including smart edge devices and systems, customer/third-party asset integration, and distributed computing and control paradigms. Information and communications technology is foundational for further convergences in the following:
    - Networking—multiple tiers of communications requirements (Open Systems Interconnection [OSI] model)
    - Processing—computing and applications
    - Representation and exchange (data architecture and interoperability)
    - Persistence—storage for data at various levels of latency hierarchy
- **Control structure**. GA treats control as a structure of its own, where the focus is on control forms and patterns, not on algorithms or theory. Control algorithms, like protection algorithms, are included in this structure class. Grid control has a strong connection to organized central electricity markets, where they exist. Specific classes of grid control can include the following:
    - Dispatch/scheduling
    - Load sharing
    - Power flow control, including protection
    - System frequency regulation
- **Convergent infrastructures**. Convergence is the transformation of two or more networks or systems so that they share resources and interact synergistically via a common and seamless architecture, thus enabling new value streams. Multiple networks have converged already with the grid (e.g., information and communications technology, financial, and market networks). Additional networks are converging or may converge, including fuel (especially natural gas), transportation, water, and social structures.
- **Coordination framework**. Coordination is defined as a set of relationships, processes, and flows that tie the grid together and enable individual parts to operate as a cooperative whole. Note that GA treats control as a subset of coordination because several coordination processes used in grid operations would not be recognizable to control engineers, since they are often business processes. While this generalization allows grid architects to deal with grid operational processes that exist outside of the grid control systems, it does have significant

interoperability requirements and is highly dependent on data alignment and the use of standards.

The structure of structures described earlier can also be viewed as a meta-control structure. The coordination framework can be a collection of structures or a new structure in itself. The coordination framework can be defined, hidden within other structures, or can be missing entirely prior to GAMUT Tool user interactions.

2.2.2 Quality, Property, and Component Mapping Process

System **qualities** in GA represent system-level behavior reflective of the consumer (user) and stakeholder viewpoints. An example previously provided in GA is a house electrical installation providing utility at the consumer level, where the quality is utility of electric energy. Further details are abstracted. System qualities require properties to deliver the necessary functionality.

System **properties** in GA represent the provider viewpoint—the externally observable behavior and functionality of system elements. System properties may arise from one or more **elements** and their relationships. An example is house electrical breakers (element) contributing safety (property) for the house electric supply (quality).

GAMUT distinguishes between various system-level views and therefore various sets of objectives. A GAMUT user can provide System of Interest (SoI – here meaning user-specific scope/project) objectives (primary source), although it is also possible to extract default (most common) system-level objectives from reference models (a set of default system-specific “objectives”). Having a set of objectives helps determine what system-level qualities must be present to allow those objectives to be accomplished. An example from (JD Taft, 2020) is shown in Figure 4. System qualities emerge from component properties. Notably, properties are themselves emergent from components (nodes in a structure) and their relationships (edges/connections in a structure) and usually contribute to many system-level qualities. Properties are not observable at a system level, so structures need to be established before mapping can take place. Again, information from the user, the user’s SoI, and reference models can be used to establish initial mapping. Properties can be mapped to specific components to finish a traceable chain of dependencies, indicating which system-level quality relies on which components in the structure.

With GAMUT, the exact objectives or system-level qualities are often unknown. In this case, an alternative route can be taken. GAMUT will use SoI information in combination with reference architectures to imply and estimate SoI structures and their components. Establishing the SoI structure enables mapping to properties and potential system-level qualities that could be enabled (as well as gaps such as missing properties for specific qualities). The set of qualities is information that can be reviewed by the user and/or verified with the original GA route or compared with user objectives, needs, and policy constraints.

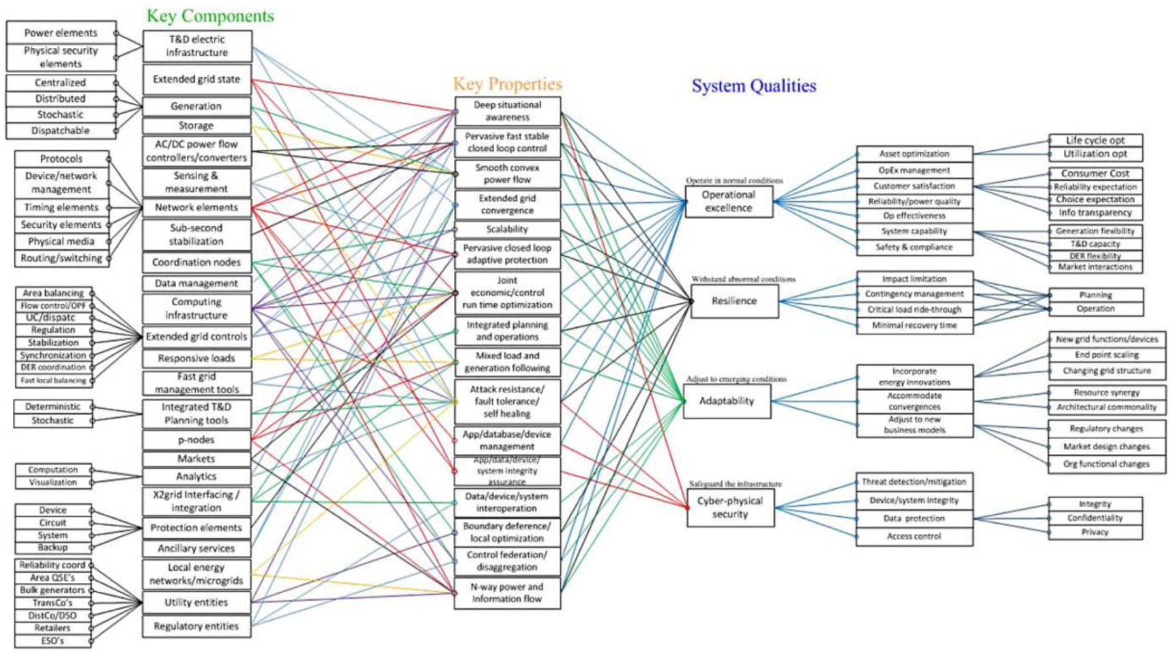

Figure 4. Extended quality-property-component mapping (JD Taft, 2020).

The following key points help with the property-to-quality mappings that would be captured in the GAMUT internal knowledge base (JD Taft, 2020):

- Properties can be connected to qualities via mappings
- Property-to-quality mapping is a two-layer structure
- Mappings are many-to-many but not all-to-all (in general)
- The mapping links can be binary (1 or 0; present or not) or they can have a numerical attribute

The following key points help with mappings of elements (i.e., key components and structures) to properties:

- Elements can be connected to properties via mappings
- Element-to-property mapping is a two-layer structure
- Mappings are many-to-many but not all-to-all (in general)
- Mapping links can be binary (1 or 0; present or not) or they can have a numerical attribute
- The combined element, property, and quality map is a tripartite graph

Mappings span across GA structures and therefore provide composite structure views, with components from various structures. In other words, information gathering may follow a structure-by-structure approach. However, the output is a composite structure, intertwined through system-level mappings from quality to property to component.

The output of the process yields perspectives from multiple analyses, such as SoI feasibility analysis, theoretical and analytical studies on structures and components, and use case concept testing studies. In a perfect case scenario, a well-defined composite structure of SoI in combination with a GA knowledge repository can enable simulation capability, where an instantiation of SoI within GA can run as a state machine, propagating change and analyzing architectural decision impacts on the entire system. GAMUT then uses this output information to generate its output notes/feedback/conclusions for the user.

Another relevant aspect of mapping is that well-defined architectures can be compared for alignment, establishing a score for SoI fit to a larger system. GA describes this process as calculating the “angle between two architectures.”

2.2.3 Modified Architecture Development Process

The GA approach is designed to expose the structures that exhibit system-level qualities and properties. Simplified, the approach is built on understanding main objectives, deriving system-level qualities, and exploring scenarios to create structures that are representations of components with properties and relationships. This process then gives rise to architecture in a GA context. The glue that holds architecture development steps together is the notion of qualities, properties, and components. Mapping between these concepts is key for many GA value propositions, and this approach could also be used by GAMUT. System quality, property, and component mapping ensures that components between different structures can be mapped in various views (contexts) and ensures traceability that can be verified.

The GA approach described in (JD Taft, 2020) represents a very high abstraction level, almost generic when possible. This provides a dichotomy for the GAMUT project—the GA process is broad and abstract, whereas the system-of-interest problem scope is very specific and clear. Crucially, the qualities/properties/components mapping process (JD Taft, 2020) includes a reverse approach, which makes it useful for addressing the difference in perspective between users and architects. In the reverse architecture development process, the starting points are structures and components, and the end points are system qualities.

Figure 5 depicts an adapted (JD Taft, 2020) representation of a typical GA process and a reversed representation (GA “analysis view,” where qualities are the final product). Both processes are connected through the reversed mapping process. The original GA development process starting point is indicated at “user needs and public policies,” and in the GAMUT approach, we can add another starting point at the architectural elements level, containing information about structures, components, and their properties. In this scenario, there should be enough information from the user’s SOI to possibly begin at both points and validate the products when the loop is closed. System qualities that are derived from SOI structures and components (“GAMUT Start”) must be compatible with “user needs” and relatable to system qualities derived directly from user needs.

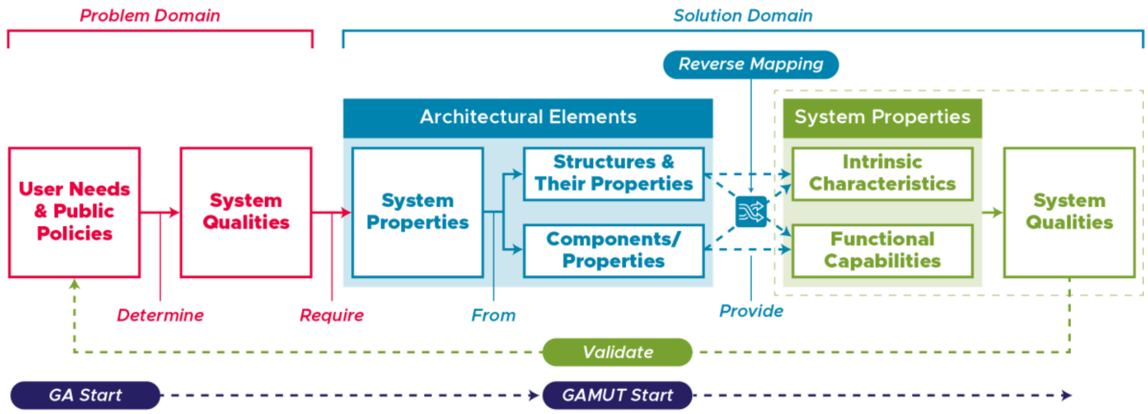

Figure 5. Grid architecture development and system quality development processes.

Next, we look at gathering the information necessary to initiate the mapping. Necessary information can be obtained through various mechanisms, like using reference models. Section 3.0 covers the knowledge management aspect in more detail. It is worth looking at the mapping process as it is laid out in GA and what modifications a GAMUT Tool needs to accommodate.

3.0 Documentation Framework

The documentation framework in the GAMUT context includes the life cycle of documents and other knowledge artifacts and relevant approaches and tools for supporting GAMUT objectives. This section provides examples of various knowledge sources and knowledge management approaches that can be useful for GAMUT.

3.1 Documentation and Knowledge Management

During GAMUT project planning and execution, the team adopts an informal systems engineering life cycle process to ensure a systematic approach and mitigate project risks. Initially, information on requirements, needs, and expectations is gathered to fully comprehend the problem domain before finalizing the solution architecture. The initial black box system structure is shown in Figure 6.

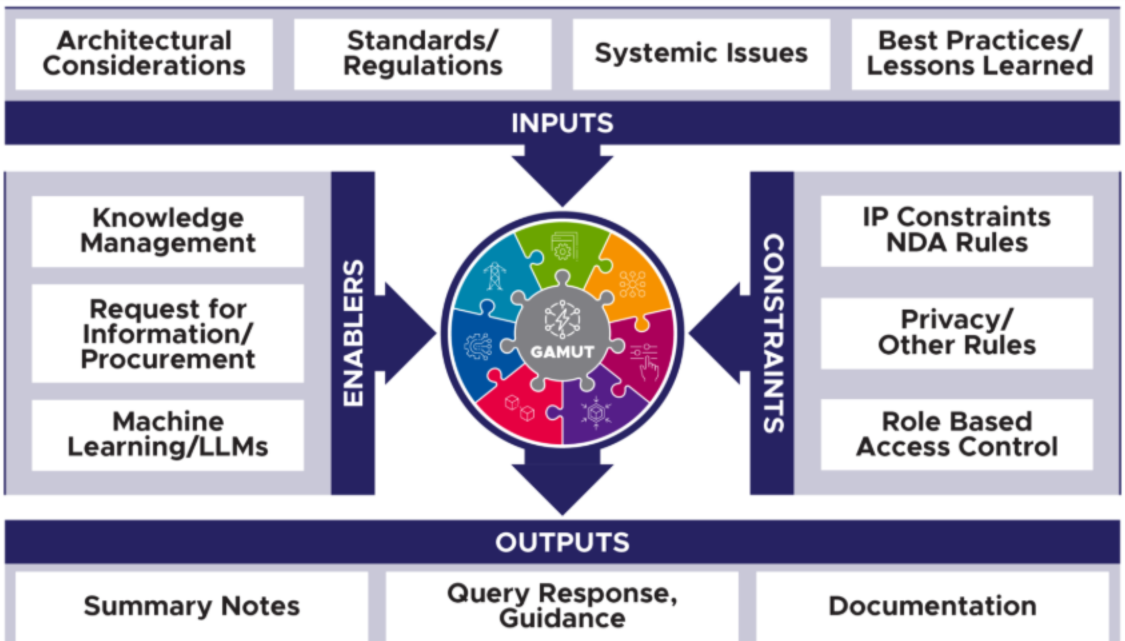

Figure 6. Systems engineering approach to “product system” definition[1].

The individual components of the approach are described in more detail in subsequent sections. Additionally, we capture the initial content related to these topics. The “inputs” section covers any information that needs to be processed by the GAMUT Tool and includes any potential tool use or applied external methodologies/approaches. Most inputs can be provided asynchronously/offline as part of the knowledge base buildout. Defining and capturing information for the “output” section ensures that the GAMUT Tool produces the necessary information/artifacts to satisfy stakeholder expectations and needs. The “enablers” and “constraints” capture relevant information from adjacent systems that can either enable additional functionality/opportunities or limit system operation (e.g., laws and regulations). Development of the GAMUT Tool will use this approach to capture the entire system and avoid silos. The efforts

[1] See the “GAMUT Concept Document.”

are expected to be continuous throughout the project life cycle and as more information becomes available.

Knowledge management is a well-established discipline that facilitates the collection, organization, sharing, and analysis of knowledge. The envisioned GAMUT Tool can leverage the latest developments in software tools as well as the developed knowledge that is available through GA, technology standards, and other materials. The choice of knowledge management approach and tools dictates the information organization within the GAMUT Tool. The actual approach is determined as part of the feasibility study, which includes an assessment of multiple use cases to evaluate various engineering tradeoffs associated with these approaches.

For example, a graph-based knowledge management approach offers beneficial outcomes for managing information and making it accessible to GAMUT's users. These approaches offer strong capabilities for illustrating the connection/interdependency between data points and integrating diverse data types, potentially offering a good starting point for automatic software tool integration (e.g., retrieval with a large language model).

To better understand the necessary identification, capturing, storing, maintaining, accessing, and disposing of knowledge/information/data, the team takes a closer look at the already-identified information clusters and specific databases, with the feasible knowledge management approaches.

To manage information identification, gathering, and access, it is useful to establish a systemic approach early on and define the conceptual GAMUT Tool element for data management. The GAMUT Tool is expected to use many such elements that can be managed independently through the interfaces identified as well as specialized approaches for each data/information type contained within the element.

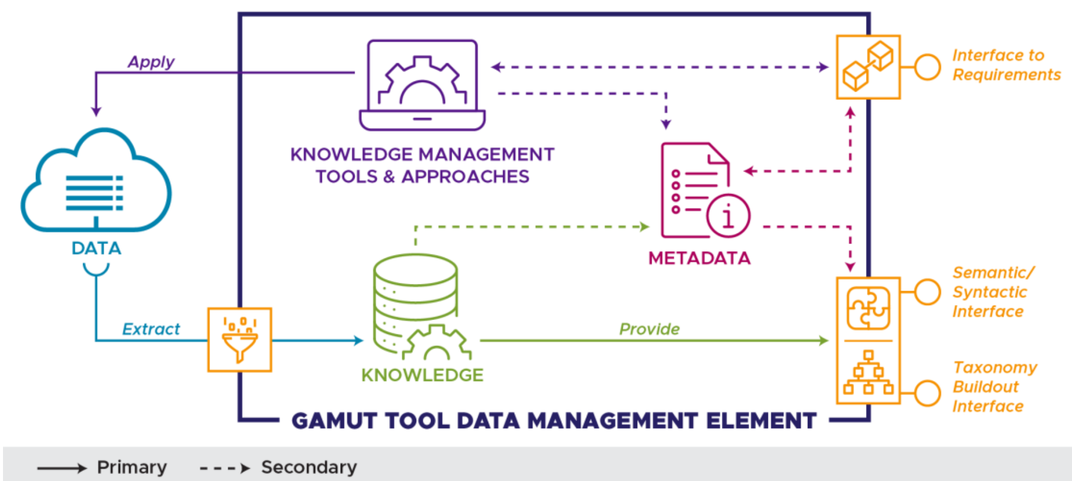

Figure 7. GAMUT Tool data management element definition.

Figure 7 depicts the systemic approach to knowledge extraction and management by defining the GAMUT Tool knowledge management element and its interfaces. The primary interfaces and data flow are indicated with solid lines, while dashed lines denote secondary information flows (metadata gathering) The source data (raw datasets, documents, etc.) are out of scope for GAMUT (instead of storing all data as a database, the approach is to store the knowledge about the structure and the metadata for accessing the source data). An interface can be specified in the interface control document to describe data acquisition on how specific data types can be processed in GAMUT. Knowledge management tools and approaches are applied to source datasets to extract knowledge. Knowledge may be stored within the element, according to a specific taxonomy (data structure) to preserve unique dependencies and domain-specific knowledge. Captured information, tools applied, and requirements invoked/satisfied within the element are captured in the metadata that is linked to the GAMUT Tool requirements (ensuring traceability and transparency). The main part of the GAMUT Tool data management element is the interface to “taxonomy buildout,” through which the semantically meaningful information is retrieved for GAMUT operation. The GAMUT Tool data management element for each structure-specific data can be imagined as a vertical slice of Figure 2—the taxonomy buildout, knowledge management tools, data bases, and technology/domain specific knowledge base, where the technology specific layer represents the data interface.

3.2 Knowledge Management Methodology Approaches

GAMUT relies on knowledge management approaches and successful various domain knowledge integrations. The capability to sufficiently decompose GA main structures and principles and apply them to other sources of information and knowledge is directly affected by the selected knowledge management approach. This process also must also be performed in reverse, assembling the information from the technology specific layer into the GA structures. To understand the process and be able to assess the feasibility of developing such a tool, the GAMUT team identifies the following process of selecting a knowledge management approach:

1. Identify the structures and methods in GA literature and materials to be used in GAMUT for knowledge database buildout.
2. Identify the functional requirements and scope for knowledge management tool selection.
3. Analyze the available state-of-the-art examples of already deployed technology, information databases, GA materials, the standardization landscape, and other available relevant information, including through stakeholder interactions. This process accounts for information decomposition feasibility and readiness level for knowledge management technique applications.
4. Analyze technology stack approaches and alternatives. Determine the usefulness of the data/information/knowledge management technology in previous steps.
5. Iterate on steps 1 through 4 for all of the candidate materials, techniques and technologies. Once this analysis is complete, move to step 5.
6. Develop a knowledge harvesting strategy and define its scope.
7. Design a knowledge management architecture for the GAMUT Tool including an enterprise governance strategy for knowledge management maintenance. The following are the core components for knowledge management systems:
    a. Modern database architecture stack
    b. Content management
    c. Metadata catalog
    d. Thesaurus
    e. Taxonomy schema
    f. Knowledge graphs

   g. Data schemas
      i. Time series
      ii. Geospatial
      iii. NoSQL
      iv. SQL
      v. Semi-structured
   h. Interoperability patterns
8. Use GAMUT Tool knowledge management concepts and establish feedback loops for technology improvements and optimization.

The following subchapters dive deeper into examples of developing a knowledge base in accordance with various vertical slices from Figure 2.

3.2.1 Example for the Geographic knowledge base

The section captures the thought process behind establishing a document (data) management framework for capturing various types of data/information/knowledge and presenting the systemic analysis outcomes in the final feasibility study. An example analysis is provided for geographical information.

The geographic information includes sources of geospatial data and information. This means that the dataset semantically distinguishes between locations, areas, spatial dimensions, and other geographically relevant metadata. An example is a Google Maps[1] type product with information on the balancing authority area and on the transformer's or generator's location on the map. This geographical knowledge base focuses on capturing the geospatial data and meaning (semantics) with the GAMUT Tool taxonomy so that the geographic context can be connected to other GA structures and data bases (e.g., the balancing authority area is captured in the geospatial data, but the meaning of "balancing authority" can be retrieved from the North American Electric Reliability Corporation functional model under the allocations knowledge pillar in Figure 2). In this approach, the user can manage geographical information by utilizing unified methods and tools across the GAMUT Tool.

[1] https://developers.google.com/maps.

3.2.1.1 Needs and Expectations

- The team wants to leverage existing spatial data sources and catalogs while preferably using open standards, formats, or nonproprietary industry best practices.
- The GAMUT Tool needs to support the widest possible analytics with advanced tooling and datatypes:
  - Vector (points, lines, and polygons)
  - Raster
  - Topographic
- The geographic dataset should also cover weather data.

Geospatial standards of interest

- GeoJSON
- ESRI Shape Files
- Open Geospatial Consortium (OGC)
  - Web Feature Service
  - Web Map Service
- ISO 19115 - Geospatial Metadata Standard
- ISO 19136 - ISO 19136 Geographic Unified Modeling Language Application Schema.
- ISO 19139 - Geographic MetaData XML (gmd)
- GeoPandas
- CSV

3.2.1.2 Example Data Flow

Figure 8 depicts alternative geospatial data solutions to support GAMUT geospatial analysis. While this diagram does not depict a specific solution space for data sources or tooling, it does reflect the advancements made within the geospatial community, providing many alternatives for GAMUT. Possible tools, protocols, and nonproprietary datatypes with flows are depicted in Figure 8.

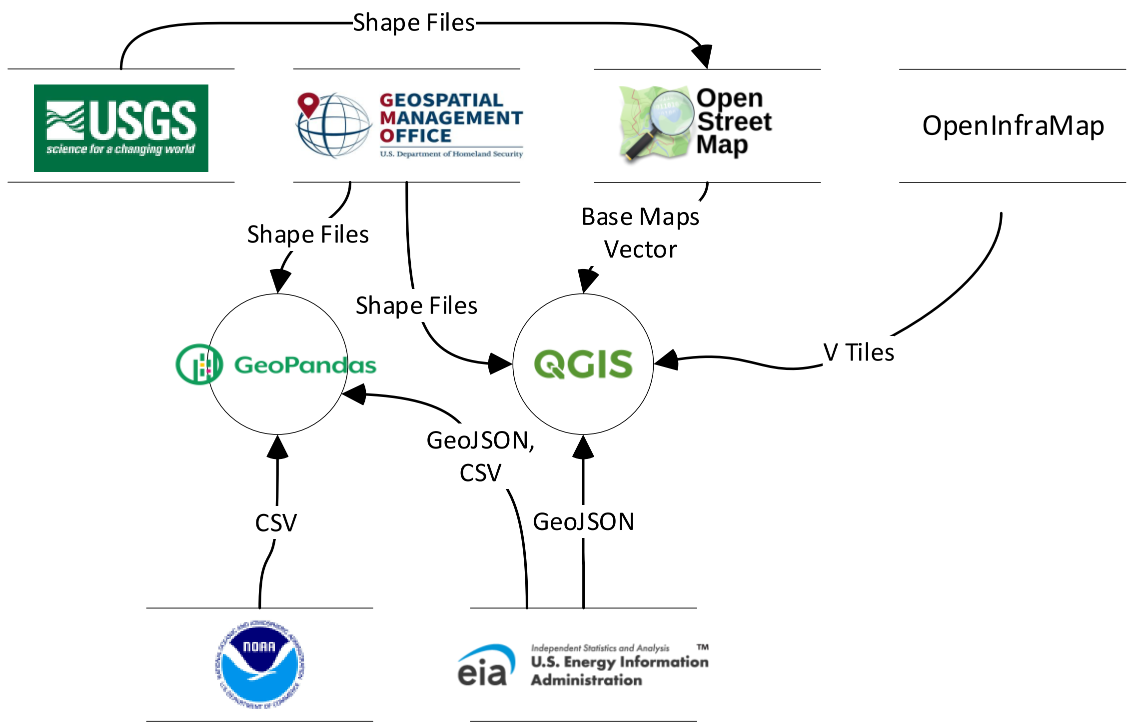

Figure 8. Geospatial data management approaches.

Pros and cons are captured for each data type and tool that the project team is considering. The outcomes of the analysis are integrated into the final feasibility study.

3.2.2 Example for Relevant Standardization

The standardization landscape for GA-relevant domains is vast and encompasses not only technology but also regulatory and operational aspects. The GAMUT Tool data management element approach allows the team to develop a knowledge management strategy that can be tailored specifically to a particular domain. An example is presented below for the use of a Smart Electric Power Alliance standards map.[1]

The Catalog of Standards Navigation Tool provides a snapshot of GA categories and associated standards. The map allows users to click and hover over categories to observe lists of relative standards documents available from different international communities. The website is intuitive for exploring standards and browsing, but it is limited in its ability to allow users to search for occurrences of a standard.

[1] http://gridstandardsmap.com/.

3.2.2.1 Needs and Expectations

Labeled property graphs offer one approach for building and querying machine-readable taxonomy. Labeled property graphs are graphs composed of nodes and relationships.

Additionally, the relevant metadata and linkages to relevant GA domains should be captured. Each node and edge has an identifier and can be described by numerous properties. Each property is composed of a label and corresponding value.

3.2.2.2 Example Data Flow

The SEPA (Smart Electric Power Alliance) Catalog was scraped, and an extracted portion is presented below:

- SEPA Catalog of Standards
  - Markets
    - Retail Wholesaler
      - IETF RFC-6272
      - NISTIR 7628
      - OASIS EMIX
      - OASIS Energy-Interop
      - OASIS WS Calendar-Common-Schedule
      - IEC 61968-1:2020
    - Aggregator
      - IETF RFC-6272
      - NISTIR 7628
      - OASIS EMIX
      - OASIS Energy-Interop
      - OASIS WS Calendar-Common-Schedule
      - OpenADR 2-0a
      - OpenADR 2-0b
    - Energy Market Clearing House
      - IETF RFC-6272
      - NISTIR 7628
      - OASIS EMIX
      - OASIS Energy-Interop
      - OASIS WS Calendar-Common-Schedule
      - IEC 61968-1:2020

For proof of concept, a simple Python script was generated to create category and standard nodes containing the absolute standard hierarchy for the nodes. To identify connections between the standards in the map, another script processes all nodes that contain the property label (e.g., "n.path CONTAINS '/'"). In a single query, the path is parsed, and the parent-child relationships are constructed using the second match statement. The concept was proven to be fit for the purpose of handling the catalogued data types and was thus included in the methodology .

For demonstration purposes, a subset of the graph is visualized in Figure 9. The purpose is to show the concept for relationship graph buildout from source data.

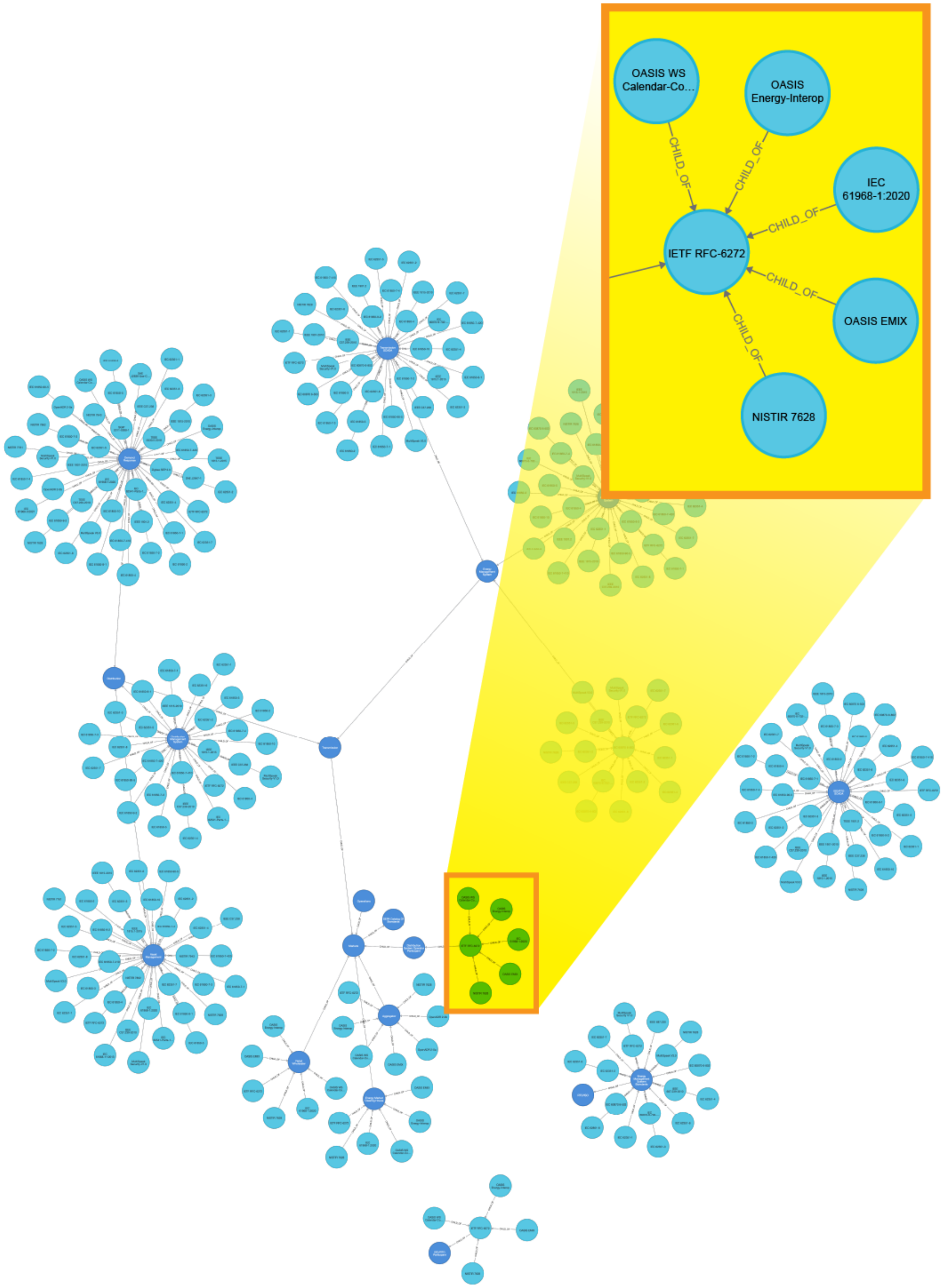

Figure 9. Partial Smart Electric Power Alliance (SEPA) standards map representation as a labeled property graph.

This representation of the standards map can be queried in at least two useful ways: following the “drill-down” approach to identify relevant standards for a particular application or finding uses for any particular standard. An example is provided below.

3.3 User/Stakeholder Engagement Framework

A significant part of the documentation framework is managing information concerning the user’s or stakeholder’s interactions with the concept of GAMUT Tool. The approach requires management of documents, databases, and various custom inputs (e.g., dialog chat conversations, diagrams, and pictures). A high-level interaction flow between the GAMUT Tool user and the tool is depicted in Figure 10. Documentation is a significant part of the interaction (depicted as the first step in the figure) and covers all documentation that can be prepared before the user directly interacts with the GAMUT Tool. In practice, this step would be automated, but it is currently regarded as a separate precondition step.

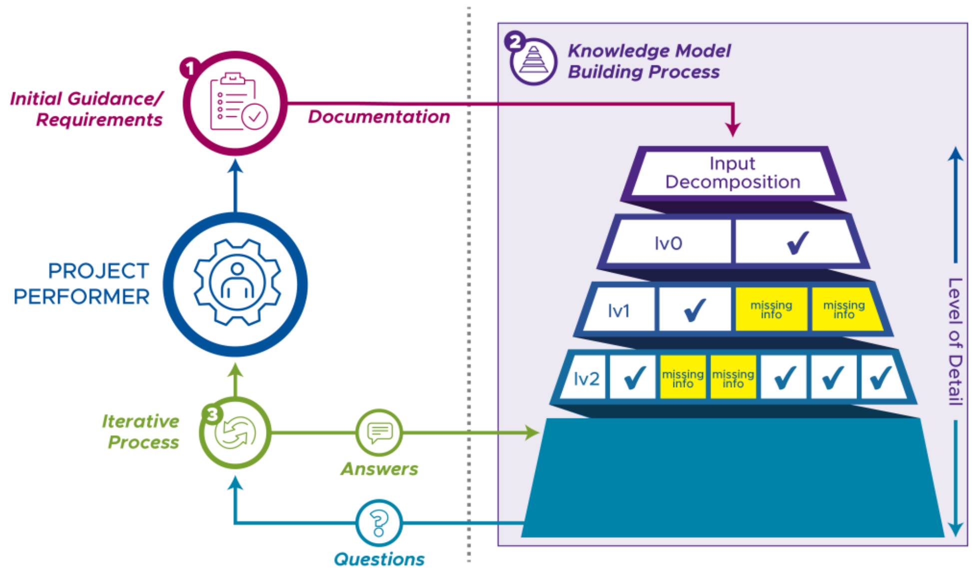

Figure 10. GAMUT conceptual user interaction architecture.

Stakeholder engagement and case study efforts are underway in parallel to examining various data types, formats, queries, and overall approaches to better understand the needs and requirements for GAMUT Tool operation. Step 1 in documentation process involves the following aspects:

- Project/technology deployment relevant documentation
- Notice of Funding Opportunity (NOFO) information
- Proposal (if available/shareable)
- Project partners and stakeholder list
- Datasheets
- Statements of work (if available)
- Project requirements (if available)
- Component lists

- Other materials

Step 2 of the documentation process is to provide answers to a predefined questionnaire that is intended to evaluate the project from the highest abstraction level perspective, as well as seek understanding of the overall technology approach and the concepts of operation. The questionnaire form (Figure 11) is prepared as a separate document/form. Digital form can be a part of GAMUT Tool in production.

After the information captured in the documentation stage is decomposed and mapped to the GAMUT Tool taxonomy. Step 3 is the iterative Q/A process. During this process, the user can use initial information obtained (notes, summaries, links, etc.) to prepare additional queries.

Term	Possible Values	Notes
Project Lifecycle Stage	☐ Early stage (concept/planning/pilot demonstration) ☐ Mid stage (deployment) ☐ Late stage (maintenance) ☐ End of life (disposal)	Click or tap here to enter text.
Power System Service Area	Enter if known. Click or tap here to enter text.	(e.g., PG&E, Western Interconnection, Eastern Interconnection)
Program Stakeholders	Enter if known. Click or tap here to enter text.	(e.g., DOE, "Dominion," "ABB")
Value Capture Mechanism	☐ Market ☐ Cost Recovery ☐ Deferred Cap-Ex ☐ Other	Click or tap here to enter text.
Technology Domain	☐ Transmission ☐ Distribution ☐ Generation ☐ Load (consumption)	Click or tap here to enter text.
Interaction Model (OSI) (all that apply, if applicable)	☐ Application ☐ Presentation ☐ Session ☐ Transport ☐ Network ☐ Data Link ☐ Physical	If the tech/project has significant interfaces to other systems, please indicate the level. (at which level the tech would integrate into larger systems.)
SGAM Interoperability Level	☐ Business layer ☐ Function layer ☐ Information layer ☐ Communication layer ☐ Component layer	https://syc-se.iec.ch/deliveries/sgam-basics/

Figure 11. Example of GAMUT questionnaire.

The questions are designed to understand the project from various aspects and architectural frameworks that are applicable in the industry. When the stakeholder is more familiar with one framework than another, the team can use that framework to narrow down the more specific aspects of the technology and the project.

The second part—stakeholder interviews (or Q/A sessions)—is guided by the information provided and initial GAMUT Tool analysis results. The goal is to address any gaps and identify areas of interest and potential value-add. In this context, value is GAMUT Tool responses that are relevant to the user as well as lessons learned and stakeholder feedback for the GAMUT project team.

3.4 Information Hierarchical Structure

An important part of the knowledge framework is the ontology, which formally defines the key concepts and relationships by using controlled language to organize and represent domain knowledge. An ontology that serves as the basis for many domain-specific ontologies is referred to as an upper ontology. Using an upper ontology as the basis for defining domain ontologies provides more opportunities to cross-reference concepts between domains. Modularity is a hallmark trait of upper-level/domain-based ontologies.

Ontology – a set of concepts and categories in a subject area or domain that shows their properties and the relations between them.

Taxonomy - a system of classification.

3.4.1 Formal Upper Ontology Approach

The "basic formal ontology" [1] is an example of an upper or formal ontology. It provides the most general categories for describing reality, like continuants (things that endure through time) and occurrences (processes or events that unfold over time). A basic formal ontology is specified in formal language and includes textual definitions, like an "Web Ontology Language" [2] (OWL-2) axiomatization[3], and a first-order logic axiomatization to ensure logical rigor. First-order logic axiomatization is complex and requires that domain ontology implementers have extensive experience, preserving this rigor so that reasoning-based rules can be used to detect and infer implicit relationships within the ontology. This forms a new requirement if basic formal ontology is used. Using formal ontology has the advantage of providing a method for reasoning. However, curating and maintaining domain ontologies based on formal ontology is time-consuming, requires domain and description logic expertise, and is difficult to perpetually fund to retain a high level of standard. That withstanding, there are examples of formal ontologies which have been standardized such as ISO/IEC 21838-2:2021 which is recognized for its ability to support global information technology and provide consistent architecture for formal vocabularies. Recent advances in agentic AI may relieve some of the maintenance risks associated with formal ontology use.

3.4.2 Multitier Vocabulary Approach

Another way of achieving a pattern similar to upper-level ontology/domain modularity is more focused on the preservation and reuse of clearly defined terms than on preserving ubiquitous formal logic. The trade-off is that effective solutions must curate consensus-based terminology. Consensus-based solutions rely on long-standing active communities motivated by the reuse and interoperability of technologies. The National Information Exchange Model (NIEM), Schema.org, and GIST[4] are three approaches to providing an upper ontology.

[1] See https://basic-formal-ontology.org/.
[2] See https://www.w3.org/TR/owl2-overview/
[3] Axiomatization is the formal process of reducing a body of knowledge, theory, or mathematical system down to a fundamental set of axioms, i.e., principles.
[4] See https://www.semanticarts.com/gist/

3.4.3 Ontology Life Cycle Management

Ontologies can be effectively managed in a GitHub code repository through the use of GitHub's version control features alongside collaborative project management tools. A typical approach involves organizing the ontology source files, such as LinkML, OWL, or Resource Description Framework (RDF) files, in a structured directory within the repository. Developers and curators work on branches to propose changes, facilitate reviews through pull requests, and enable automated continuous integration testing to check for logical consistency and adherence to quality standards. The repository can include documentation, issue tracking for change requests, and project boards to manage editorial and technical workflows separately. By integrating ontology engineering tools and templates with GitHub workflows and actions, teams ensure repeatable build and release processes, maintain change histories, and encourage community participation. This setup promotes transparency, collaboration, and rigorous quality control throughout the ontology life cycle, making GitHub a practical platform for distributed ontology development and maintenance.

3.5 Data Catalog Considerations

A data catalog is an approach to capture inventory of information. The catalog provides context so that data can be discovered, understood and utilized. In combination with knowledge graph the resulting capability enables emergent knowledge capturing through graph associations and information (not necessarily detailed data itself) is stored in a machine-readable and searchable format. Data catalog is the inventory list, and the knowledge graph captures how information is connected. The two main requirements for consideration here are machine readability and ability to provide knowledge management in a potentially unstructured form. We envision a data catalog process as shown in the Figure 12. A catalog is a web of metadata records used to describe interconnected information resources.

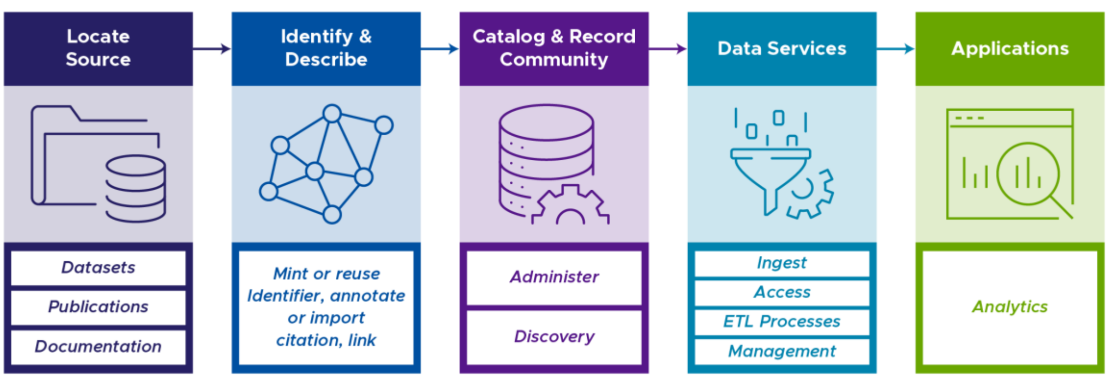

Figure 12. Potential GAMUT Tool data catalog process.

The data catalog process captures multiple stages that are crucial for knowledge capture. We note that knowledge is not data and implies more semantic content that can be applied in context. Retention of context is critical. Therefore, the "identify/describe" stage is key for ensuring linkages, descriptions, and knowledge mapping.

4.0 Feasibility Assessment Methodology

The purpose of the feasibility assessment is to understand resource needs and technology readiness for GAMUT Tool development. The methodology must assess the feasibility against the requirements and expectations. The assessment may be qualitative and/or quantitative, depending on the methodologies used. A systematic approach involves a combination of both types of assessments.

4.1 Feasibility Assessment Overview

There is no single methodology that is universally used for performing a feasibility assessment. The team can reverse-engineer the method, starting with project success criteria and requirements, by analyzing the success probability for each element as well as the emergent behavior of the entire system. This is why feasibility analysis is performed during the "system analysis process" stage of the systems engineering life cycle, after the requirements and potential architecture are known[1]. The system analysis process[2] is one of the system analysis dimensions, along with cost, schedule, affordability, etc.

Figure 13, developed from the International Council on Systems Engineering's "System analysis views", shows the relevant system analysis views for the GAMUT feasibility assessment. The relevant views for GAMUT are highlighted in solid light-blue color. The top of each column shows a category name under which each of the views are highlighted (in "Resource Utilization" we select all of the views).

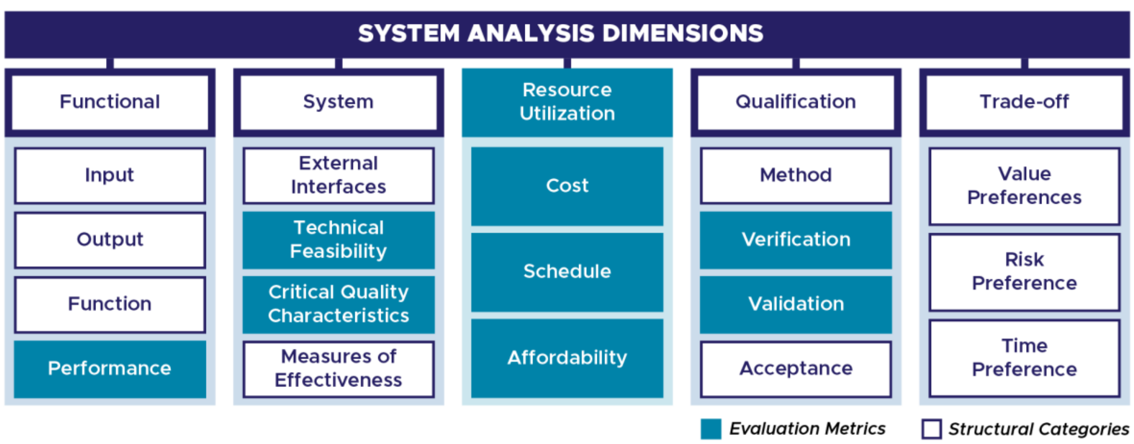

Figure 13. GAMUT System assessment elements.

The follow on feasibility study paper rates software implementation alternatives on the basis of the following criteria:

- Technical feasibility. It is important to verify that the proposed architecture does not involve impossible elements/processes/tools/approaches for satisfying GAMUT requirements. The solution is feasible when all elements and processes are technically possible.

[1] Notably, trade-off studies can be performed with multiple system architectures

[2] The *Systems Engineering Handbook* v5 by the International Council on Systems Engineering.

- Critical Quality Characteristics. Based on the Systems Thinking concept that the emergent behavior of the entire solution (GAMUT) is greater than the sum of its elements. Thus, it is important to analyze potential emergent behaviors for critical quality characteristics (security, reliability, maintainability, etc.) of the GAMUT Tool approach. Overall estimated GAMUT Tool performance is assessed as part of this evaluation in accordance with requirements . The solution is feasible if the projected characteristics meet stakeholders' expectations.
- Resource Utilization. Meeting each requirement involves costs (in terms of money and time) and the use of finite resources. The solution is feasible if the projected life cycle cost and schedule meet stakeholder expectations and the affordability criteria.
- Verification and Validation. It is important to check whether the solution is robust. The verification process assesses whether the solution meets the requirements, and the validation process tests the solution's value delivery. The solution is feasible if it is testable.
- Functional view. Different trade-off solutions may satisfy requirements at different performance levels. While a feasible solution will satisfy requirements, a performance criterion can serve as differentiator. High performance on critical requirements distinguishes a more optimal solution.

4.1.1 Technical Feasibility

Technical feasibility describes how capable the necessary technical solutions are for meeting system requirements. The team performs a technology readiness level (TRL) assessment that indicates whether the potential GAMUT Tool user would be classed as an early adopter (high risk) or a user for any given solution. A low TRL is associated with high risk, a lack of support, and low reliability.

Any concepts considered for inclusion in the GAMUT Tool feasibility assessment can be evaluated on the regular TRL scale; however, similar approaches could be used for project/technology assessments. Given the specific scope of the GAMUT approach, a more grid-focused and applied TRL system might be more useful. SM-TRL shows more applicability to evaluate user-provided project information than conventional TRL, as the projects are expected to be high on the conventional TRL level (demonstrated or deployed at pilot scales) and SM-TRL begins at step 5, considering anything less to be too high of a risk for utilities. Smart grid levels, depicted in Figure 14, represent the SM-TRL metric previously proposed for use in smart grid environments.[1]

---

[1] H. Kirkham and C. Marinovici, "Technology readiness and the smart grid," *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 2013, pp. 1–6, doi: 10.1109/ISGT.2013.6497804.

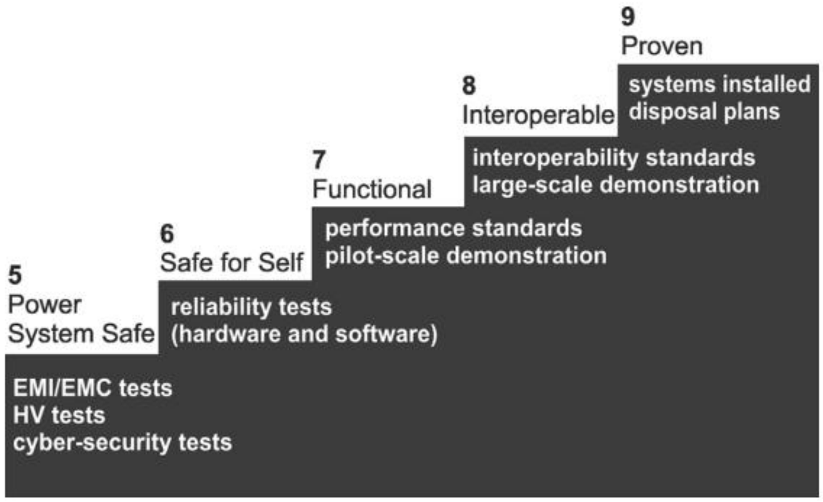

Figure 14. GAMUT System assessment process.

4.1.2 Critical Quality Characteristics

Critical quality characteristics are derived from GAMUT Tool user objectives, and requirements. Requirements translate to specific characteristics and features of the solution. In the GA nomenclature properties and qualities have a similar relationship where properties give rise to externally observable system qualities.

The assessment addresses whether the GAMUT Tool's externally observable qualities are consistent with the properties assigned to the technology elements and element combinations.

4.1.3 Cost

Cost has a significant negative impact on feasibility. Detailed cost sheets are not expected to be established at this point in the analysis process, but information about the costs associated with knowledge processing approaches and software tools may provide valuable insights.

An important point to note is the potential use of AI tools. These tools are part of the cost feasibility assessment, and multiple estimates are provided for various AI tools and approaches being implemented. The lifetime cost is considered in conjunction with the affordability assessment.

4.1.4 Schedule

The schedule is an important temporal feasibility aspect. Establishing an understanding of the potential time frame for GAMUT Tool development and deployment ("time to the market") is critical. Rough estimates may provide enough information to establish feasibility within the context of expectations and needs.

4.1.5 Performance

Performance encompasses the quantitative features supported, such as the number of states, number of structures, level of detail of the summary, types of user inputs that are supported, ability of the user to upload documents, and the ability of the user to ask questions about their own framework.

4.1.6 Affordability

Affordability analysis is an approach that seeks to maximize value, providing cost-effective capability over the entire life cycle. INCOSE has defined system affordability as follows:

"Affordability is the balance of system performance, cost and schedule constraints over the system lifecycle while satisfying mission needs in concert with strategic investment and organizational needs."

The affordability assessment takes into account the outcomes of the critical quality characteristics, cost, and schedule assessments to provide an indication of feasibility throughout the entire system life cycle. The use of AI tools has potential to be impactful to the affordability assessment (depending on the scope of use).

4.1.7 Verification and Validation

The verification and validation aspects of feasibility concern the challenges of proving that the right system was built correctly. For the GAMUT Tool development, feasibility is defined as the ability to develop a testing plan and technology demonstration plan without compromising other feasibility aspects.

4.2 Feasibility Views

The GAMUT Tool is designed to support a variety of stakeholders at different interaction points. Those providing input include a diverse set of stakeholders, such as technology developers, technology pilot project managers, contractors, utilities, and other jurisdictional entities. These users not only contribute information but also benefit from understanding gaps in their knowledge about dependencies and implications.

The project team considers and provides (if deemed valuable) various system views and performs the feasibility assessment analyses. In this case, the specific user profile depends on the GAMUT Tool expectations and requirements as well as on the potentially different technologies used under various implementation complexities. Identification of which stakeholder priority perspectives (views) are most feasible, and which are most complex, could inform the tool development process.

4.3 Information Collection and Management Structure

The information collection process is designed to be information carrier type agnostic. Initial collection efforts would be carried out with guidance and contributions from DOE and technology development project teams (including case studies). In the project's initial stage, the collection process is envisioned to be explorative and qualitative rather than quantitative and rigorous. Comprehensive information collection and processing approaches are planned to be part of the overall feasibility assessment.

The main sources of information are documentation and written artifacts (GA materials, standards, reports, diagrams, etc.), including the documents provided by technology project participant teams (technology descriptions, lessons learned, reports, etc.). Other significant sources of information include case studies and interactions with the providers of specific grid solutions. This means capturing narratives and information that are not well documented or even defined—for example, lessons learned, anecdotal/systemic issues, and insights from subject matter expert interviews. For the collection process, we envision the use of a structured GA framework, as well as the development of a methodology that is a good fit for any chosen knowledge management solution.

The information inputs (Figure 10) must be decomposed into their relevant elements, according to GA structures, and must be consistent with the knowledge management framework. The decomposition process is initially qualitative for the purpose of determining the feasibility of using machine learning tools to reliably perform this task. Information that is decomposed can subsequently be retrieved through queries that are not necessarily directly linked to the initial context, producing an overall solution that is much more future-proof and manageable for GAMUT users.

All information contained in GAMUT needs to be managed to ensure security, privacy, and availability. Information management is a crosscutting process that is applied throughout each step of the information life cycle in the GAMUT project, including collection, processing, analysis, and presentation. Access to information must be controlled, especially when information is obtained through a nondisclosure agreement or other process that limits proliferation. The project team acknowledges the need to make many potentially complex information management decisions that are not obvious at the moment. The feasibility assessment includes assessment of the main decisions (e.g., information use under nondisclosure agreements, business sensitivity, and intellectual property) that affect the overall feasibility.

5.0 GAMUT Feasibility Assessment High-Level View

To recap, the main goal of grid architecture is to provide a comprehensive understanding of power grid challenges. The grid is an ultra-large-scale, dynamic, and complex system and grid architecture helps to manage the complexity of viewing the grid systems of systems in its entirety. GA is a high-level approach/method. This leads to the main challenge of GA usefulness for lower abstraction level systems – how useful can a grid architect's view be to someone involved in specific and detailed subsystems. The envisioned GAMUT Tool seeks to bridge that gap by connecting subject matter expertise across GA structures, providing valuable insights and factual materials to those who may lack GA expertise.

The GAMUT project team aims to establish the feasibility of the approach. At the system level, the expectation is for a GA baseline to be established to situate GA as the common framework linked to all grid systems and systems of systems.

The solution domain leverages existing technology and concepts in GA, knowledge management, and other relevant areas. To assess the GAMUT Tool building blocks and the overall approach, a feasibility assessment is proposed, rooted in systems engineering and GA architecture evaluation concepts.

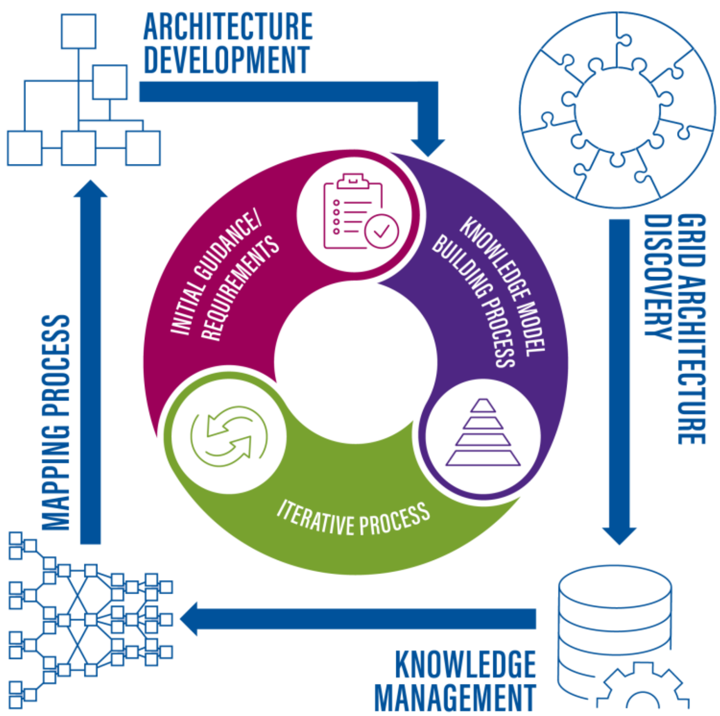

Figure 15. GAMUT conceptual approach overview.

The GA baseline represents the whole process, which ends with mapping and continues iteratively. The documentation framework is driven by the first step and the requirements from user documents, as well as the backend information gathering/maintenance/disposal requirements and solution space opportunities. Feasibility is affected by all components and must be assessed for each individual component as well as the system as a whole.

6.0 Conclusions

Previous work on GA can be leveraged to establish the GAMUT Tool development approaches. Although the concepts are useful, meeting the envisioned GAMUT Tool user expectations can be a major challenge because GA is a top-down, high-abstraction-level approach, whereas a lower level of abstraction and real-world, technology-specific problems are required.

The GAMUT Tool development approach follows GA guidance and principles wherever possible and useful. The GAMUT Tool leverages the grid structure approach and architecture buildout process while keeping it scalable (downscaling) for specific areas. Current state-of-the-art knowledge management capabilities and other software solutions are considered to significantly lower the burden for necessary grid structure context setting. A reversed architecture process can be implemented along with the knowledge context to bridge the gap between GA and system-level complexity.

The systems analysis process, based on systems engineering principles, is utilized to focus on relevant aspects for GAMUT Tool feasibility. It is important to assess the feasibility of each individual component as well as the integration feasibility of the whole solution system. The criteria defined in this document are used to assess the final feasibility.

7.0 Future Work

When applied, the methodology provides the information for the feasibility study and allows for go/no-go decision gate. A feasible GAMUT Tool development approach would warrant further investigation and development of a Minimum Viable Product of the GAMUT Tool, that could be instantiated as a pilot project.

Future work involves instantiating the core concepts of the methodology, such as the GA baselining process, solution documentation framework and assessment methods for the GAMUT Tool input evaluations.

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

www.pnnl.gov