MOTT MACDONALD

Funded by

Infrastructure Architecture Framework

A multi-sector approach to enterprise systems engineering and management

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Contents

Acknowledgements

A little over a year ago we set out to demonstrate the feasibility of establishing a common specification for an architectural framework that could support the transformation of civil infrastructure as complex socioeconomic systems. This collaborative research program builds upon trailblazing work being done, both locally and internationally, by infrastructure providers.

The goal of the project was to develop common approaches to engineering and managing infrastructure as complex socio-technical systems. It included the establishment of a functioning trans-disciplinary engineering partnership and the delivery of draft framework specifications.

Participants included the New York MTA, the New York Power Authority, the Port Authority of New York and New Jersey, the New York City Department of Environmental Protection and many other infrastructure providers, government agencies and academic institutions.

The program is being managed by the New York Academy of Sciences with advisory support led by Mott MacDonald and support from ASCE, ASME, AIChE, IEEE, and INCOSE[1]. We are extremely grateful for the leadership of Michael Salvato, the efforts of Carlos Maestre as project manager and lead enterprise architect, facilitation from the American Institute of Chemical Engineers by Michelle Bryner and Sarah Ewing and especially for the contribution from our expert working group.

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Jennifer L. Costley, PhD
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[1] ASCE: American Society of Civil Engineers; ASME: American Society of Mechanical Engineers; AIChE: American Institute of Chemical Engineers; IEEE: Institute of Electrical and Electronics Engineers; INCOSE: International Council on Systems Engineering

Executive Summary

Governance and management of infrastructure must address the intended purpose, capacities of the whole system and externally oriented outcomes.

In the last decade, there has been an explosion in the development of new standards and practices for the management of various aspects of large-scale infrastructure systems and the data they generate. Work has also focused on providing additional standards and practices recognizing the cyber-physical nature of modern infrastructure (e.g., digital twins). While standards are important, they are not sufficient and without sufficient context can, in some cases, make managing complex infrastructure more difficult.

What is missing is not more standards, but an appropriate framework for harnessing the power of existing standards to enable a system-centric transformation. Such a framework will enable the deployment of large-scale infrastructure by facilitating the communication between management, operational, engineering, and information systems. It will require the combining of a rigorous top-down systems approach with a bottom-up approach to identification of relevant standards and their interconnections.

Over the past few months, we have applied systems thinking to move from a map of individual disciplines to an enterprise system model that unveiled and enriched the interconnections between system hierarchy levels, disciplines, and standards.

The research looked at the possibility of integrating four main domains:

- Asset management
- Systems engineering
- Enterprise architecture
- Information management

It drilled into the business models, capabilities, and functions necessary for infrastructure lifecycle management and examined the data and information management models and systems engineering techniques necessary for the design and management of cyber-physical infrastructure system.

The first version of such a framework, the Infrastructure Architecture Framework, is the subject of this paper. It has been realized through the foresight and sponsorship of the United Engineering Foundation, the guidance of leading experts from the United Engineering Foundation founding members and the contributions of over forty participants engaged in the work leading to its completion.

1 Transforming Urban Infrastructure

Digital technology is driving significant changes in both the visible and less visible dimensions of an infrastructure enterprise.

1.1 Context

Our civil infrastructure is made up of many discrete facilities and systems (power stations, water treatment plants, train stations and lines, hospitals, and schools) which are designed, built, and operated more or less independently. In reality, these assets are not isolated; they are all highly connected and interdependent. Functioning infrastructure is composed of many systems that are themselves connected and interdependent. Taken together, these interconnected systems provide services that people rely on, determining the quality of people's lives; indeed, they profoundly influence society as a whole, the environment and the economy.[2]

Re-envisioning infrastructure as a platform for human flourishing, sees the interconnections of our civil infrastructure as a system of systems that "needs to last as long as we need our society to be sustained – making the whole issue of sustainability key."

Infrastructure can be used to create better outcomes for them all, ranging in impact from better service to resilience, social inclusion, and sustainability, which is arguably the ultimate outcome.

There is also a less visible, intangible dimension of infrastructure. This dimension includes the industry standards, business management systems, and information technology that must work together to enable the effective, efficient, and sustainable planning, operations, functioning, and resiliency of the visible infrastructure components. For infrastructure to work, both the visible and less visible dimensions must bring together the necessary resources, skills, and information for seamless collaboration to deliver the enterprise mission.

Applying the notion of the Fourth Industrial Revolution (4IR)[3] to the infrastructure, organizations such as the World Economic Forum (WEF), and the G20 forum for economic cooperation are encouraging the widespread adoption of technologies requiring whole system changes, both visible and less visible, across various interconnected infrastructure networks. A recent white paper defines Infrastructure 4.0 as "forward-looking infrastructure that leverages technology and information to provide high-quality environmental, economic, and social outcomes, and functions as a system within broader human and natural systems."[4]

The viability of smart, sustainable, and resilient cities depends on infrastructure systems that provide energy, water, mobility, waste, and communication services in harmony with their environment. These socio-technical systems are difficult to change and establish the

[2] Re-envisioning infrastructure as a platform for human flourishing | Centre for Digital Built Britain

[3] The Fourth Industrial Revolution: what it means and how to respond | World Economic Forum (weforum.org)

4 Infrastructure 4.0: Achieving Better Outcomes with Technology and Systems Thinking | World Economic Forum (weforum.org)

boundaries of possibility for many decades. Transforming infrastructure, in this context, is the strategy and process that an infrastructure enterprise must undergo to adopt digital technology and systems change that revolutionize the physical assets, operational processes, and business model for delivering smarter, more sustainable, and resilient outcomes for society. The systems approach to infrastructure transformation is incredibly powerful, but even more so when we engineer a cyber-physical infrastructure system of systems in harmony with the natural environment.

1.2 Architecture Vision

The complexity of today's information intensive and interdependent infrastructure systems creates the need for new tools, methods, and understanding. Combining system-based approaches and digital technology, we can reimage infrastructure and how we manage it.

Integrating digital technologies with physical assets provides new ways of generating, integrating, and using data to coordinate the resources needed to deliver outcomes from a complex enterprise. Digitalization makes these opportunities possible by unlocking value that has long been hidden in silos. To make this a reality, a new architecture framework is needed for infrastructure which recognizes the interaction between the tangible and intangible dimensions as a defining factor in a system's make-up, functioning, and performance.

Infrastructure 4.0 is characterized by the World Economic Forum as "forward-looking infrastructure that leverages technology and information to provide high-quality environmental, economic and social outcomes and functions as a system within broader human and natural systems"

Emerging international standards for integrating engineering, management, and information technology make this architecture vision feasible. Adopting best practices provides organizations with the necessary frameworks for integrating physical assets, information technologies, and management systems. These techniques can help the enterprise deliver outcomes efficiently and connect seamlessly to the supply chain and other external systems.

In practice today, most infrastructure is managed through a siloed, project-centric lens, typically not following a more integrated systems approach to lifecycle management. Historically, organizations have focused on individual parts of the systems they manage – asset delivery, operations, management.

Implementing new standards, practices, and technologies at the project level often lacks the institutional support at the enterprise level needed for adoption of innovation across the organization and into the supplier chain.

New approaches to support enterprise transformation are needed to develop the capacities of the whole system to deliver strategic, externally oriented outcomes, as well as improve the integration of individual projects and assets into the system. By working at an enterprise scale, organizations can enhance their capabilities to improve business processes and overall outcomes with digital technology.

New transformational business models, based on enterprise management systems, information management, and integration of cyber-physical systems, recognize infrastructure as complex socio-technical systems, and require a new way of working built around systems thinking and enabled by emerging technology. A system-based approach to infrastructure delivery and management is essential to meet the needs of society today and into the future during a period of rapid technology transformation and climate change.

2 Architecture Approach

The Infrastructure Architecture Framework (IAF) represents common conventions and practices for architecture descriptions within the civil infrastructure domain and stakeholder community.

2.1 Intentions

This project views civil infrastructure as a complex socio-technical enterprise with multiple internal and external interconnections at the organization, process, information, and technology levels. The definition by Ronald Giachetti, the Dean of the Graduate School Engineering and Applied Science at the Naval Postgraduate School, highlights the socio-technical nature of an infrastructure enterprise and its ability to be adaptable to changing circumstances.

An enterprise is a complex, (adaptive) socio-technical system that comprises interdependent resources of people, processes, information, and technology that must interact with each other and their environment in support of a common mission.[5]

The human is a significant, distinguishing characteristic of an enterprise as an evolving socio-technical system.[6] To survive, an enterprise must develop external offerings and internal mechanisms to fulfill its intended purpose and continuously transform itself to perform its operations effectively and efficiently in a changing environment.

> The IEEE defines an architecture as the structure of a system, based on its components, relationships, environment, and the principles maintaining its design and evolution.
>
> The art of architecture is to provide the right level of detail for the purpose at hand of describing what an infrastructure system does, its core engineering and management functions and set out an agreed-upon taxonomy and rulesets as a framework.

Enterprise Systems Engineering (ESE) is an emerging discipline that focuses on the frameworks, tools, and problem-solving approaches for dealing with the inherent complexities of the enterprise.[7] As a discipline, it includes a body of knowledge[8], principles, and processes, tailored to the role of enterprise systems engineers, who design and build enterprise systems including less tangible and human dimensions. We are specifically looking at systems engineering approaches to the integration of business process, information systems, and engineering practices within and across entities to enable the digital transformation of infrastructure.

Enterprise Architecture (EA)[9] is one of the core processes in enterprise systems engineering used to visualize the whole enterprise, its parts, and interactions between those parts. Enterprise architecture is one of the tools used by enterprise systems engineering to support the

5 Giachetti, R. E. 2010. "Design of Enterprise Systems: Theory, Architecture and Methods." CRC Press.

6 Ibid

7 Enterprise Systems Engineering - SEBoK (sebokwiki.org)

8 Guide to the Systems Engineering Body of Knowledge (SEBoK)

9 ISO/IEC/IEEE 42010: Defining "architecture" (iso-architecture.org)

transformation of infrastructure systems. An architecture framework provides the minimum set of principles, practices, and requirements for creating and using artifacts describing the system's architecture.[10,11]

The **Infrastructure Architecture Framework (IAF)** is primarily an architectural descriptive exercise, rather than a system engineering process. The intent of this project is to take an architectural approach to define the structure, rule sets, and their relationships bringing a coherent view of the whole infrastructure enterprise. The broader ESE processes such as capabilities analysis, technology planning, enterprise integration, and stakeholder engagement are outside the scope. However, they have future potential for investigation on application to complex, technology intensive civil infrastructure systems.

The intention of this project was to identify standards and practices for aligning the business strategy and enterprise architecture of, and the management of changes to, civil infrastructure. The Infrastructure Architecture Framework (IAF) represents common conventions and practices for architecture descriptions within the civil infrastructure domain and stakeholder community. This requires the ability to visualize the enterprise as system and the domain knowledge of infrastructure management and engineering.

The IAF provides the structure to address the work ahead, a conceptual model to allocate the intellectual and organizing efforts necessary for the design and deployment of the infrastructure system, and the "in-scope" or boundaries to contain and minimize the complexity and ambiguity of its management.

2.2 Key Questions

In developing the IAF, we posed four key questions. They helped identify standards and practices for aligning the areas required to deliver smarter, more sustainable, and resilient social, economic, and environmental outcomes from civil infrastructure systems. These areas are business strategy, enterprise views of business, information, technology capabilities, and the management of change.

The key questions were:

- What are the business models, capabilities, processes, and functions necessary for infrastructure systems lifecycle management?
- What are the data and information management models, capabilities, processes, and functions necessary for infrastructure systems lifecycle management?
- How should the integration of management, information, and engineering systems be addressed within the Infrastructure Architecture Framework?
- What are the models, capabilities, processes, and functions necessary for the management of change (MoC) of infrastructure systems?

The key questions are focused on the less visible, soft systems for managing civil infrastructure outcomes, capabilities, information, and engineering services. There is a myriad of standards

[10] Enterprise architecture framework - Wikipedia

[11] Architectural Frameworks, Models and Views | The MITRE Corporation

used for the design of operational, information, and engineering technologies in physical infrastructure systems and more broadly smart cities. International organizations such as the International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), and Institute of Electrical and Electronics Engineers (IEEE) are leading international initiatives to ensure open, interoperable, supplier neutral standards for the design and operation of information and communication systems for smart, sustainable cities.[12,13,14] The intent of IAF is to describe the less visible enterprise context and operating space that defines the purpose, functions, services, and governance required throughout the lifecycle for the physical technical systems.

2.3 Guiding Principles

2.3.1 Infrastructure services for people

The purpose of infrastructure is to provide the services upon which people and communities depend on for their social, economic, and environmental well-being.[15] Infrastructure systems are highly integrated collections of subsystems that are organized to deliver services in a way that is sustainable, secure, and resilient. A service orientation is a way of thinking about infrastructure in terms of the outcomes enabled by the integration of operations, information systems, and physical asset intended to support human activities. Sustainable and resilient outcomes for people and planet translate into clear requirements for infrastructure systems and targets that cascade through the whole enterprise that allows it to maintain its viability in harmony with the natural environment.[16]

2.3.2 Data is a Public Good

A fundamental principle of the IAF is that data is a public good - something that must be shared between infrastructure owners, stakeholders, and the public. We want to encourage and empower people working in the civil infrastructure domain including any person with good ideas, to explore the data and use it to innovate, test new approaches, and develop new technologies. Data can provide significant economic benefits. Having better data leads to more productive and optimized outcomes from infrastructure. The public can derive significant improvement in cost, value, and environmental performance through the use of sharable asset information.[17] Sharing data, with the appropriate security and privacy arrangements, can catalyze innovation and improve user experience.[18]

2.3.3 Information Management is Essential

Better information management is key to delivering more value from infrastructure than physical systems alone. Data and information are only useful and valuable for an enterprise when enabling effective and efficient management of an asset, product, or service. A formal

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[12] IEC - White Paper > Orchestrating infrastructure for sustainable Smart Cities

[13] https://www.iso.org/sites/worldsmartcity/

[14] https://smartcities.ieee.org/about

[15] flourishing-systems_revised_200908.pdf (cam.ac.uk)

[16] How to use the Project 13 enterprise model (Mott MacDonald)

[17] Information-Management-according-to-BS-EN-ISO-19650_-Guidance-Part-1_Concepts_2ndEdition.pdf (ukbimalliance.org)

[18] https://nic.org.uk/app/uploads/Data-for-the-Public-Good-NIC-Report.pdf

mechanism is required to ensure the right information is available to the right people at the right time. Information management practices offer a framework for identification, optimization, custodianship of information, and information-intensive processes to innovate, generate stakeholder value, and thrive in an era where information is a core business asset and an economic good. Getting the basics of information management right is an essential starting point of the IAF for realizing the value of data at the heart of the modern enterprise and key to sustainable development.

2.3.4 National and International Standards

To work, information intensive infrastructure requires agreement on national standards, to ensure interoperability between systems and the interchange of information between organizations. There are many standards for integrating and managing complex infrastructure systems. ISO 9000, ISO 55000, ISO 19650, and ISO 15288 are common management systems for the delivery, operations, and maintenance of infrastructure. ISO 37101 is a new international standard specifically intended to help communities become smarter and more sustainable through the implementation of strategies, programs, projects, plans, and services, and to demonstrate and communicate their achievements. IAF supports integrated management systems that combine all aspects of an enterprise system, processes, and standards into one smart system. The integration of asset, information, and engineering management systems is essential to delivering the benefits of Infrastructure 4.0.

2.4 Infrastructure System of Interest

Infrastructure systems are often separately developed, owned, and managed. They are also dependent in varying degrees on the other infrastructures. The whole system is sometimes called a system of systems.[19] Interoperability is key to managing systems of systems. It can only be guaranteed through open standards and industry frameworks, ensuring that components from different suppliers and technologies can interact seamlessly.

The scope of this research is public and private infrastructure enterprises provisioning the energy, transportation, clean water, and waste management services that sustain the social and economic activities of the city. The system-of-interest, e.g., the system that is the focus of the IAF, is the enterprise, containing system elements, system element interconnections, and the environment in which they are placed, typically determined relative to the authorization boundary.[20]

The research engaged a community of practice focused on the organizations that provide energy, water, and transportation services for the New York metropolitan area, one of the most populous urban agglomerations in the world, with over 18 million people. Infrastructure organizations in the region include the NY State Metropolitan Transportation Authority, the Port Authority of New York, and New Jersey, New Jersey Transit, Amtrak, New York Power Authority, ConEd, National Grid, and PSEG. The IAF offers a common language amongst the

19 https://www.sebokwiki.org/wiki/Systems_of_Systems_(SoS)

20 https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-160.pdf

community of practice for describing effective operations and interoperability of infrastructure systems, and enterprises within the wider regional context.[21]

2.5 Infrastructure Architecture Framework Requirements

The goal is to produce a specification that:

- Focuses on externally oriented, system outcomes, not project level outputs
- Focuses on the entire enterprise, from many different perspectives, and with a multidisciplinary and iterative approach, not the constituent parts
- Aligns disciplines such as asset management, enterprise architecture, information management, and infrastructure systems engineering
- Integrates and amplifies standards and bodies of knowledge to make them applicable to civil infrastructure
- Avoids isolation of, and organizational resistance to, practices such as ISO 55000, ISO 19650, and ISO 15288
- Transcends the traditional project-centric approach and rather evolves into a modern enterprise architecture and systems engineering approach (with their language, processes, tools)
- Supports the transformation of New York civil, urban infrastructure as a system.
- Potentially forms a basis for other metropolitan areas that need a framework for coordinating their urban infrastructure systems, across multiple organizations.

21 Community of Interest and/or Community of Practice | The MITRE Corporation

3 Architecture Framework

Under the described approach and structure of the IAF, listed below are the subdomains that have been selected. The IAF global experts and community provided the design input for these subdomains.

Rather than an expanded, detailed description of each subdomain, this section focuses on the elements of commonality and interrelationship between all these components. Additionally, it considers their meaning to the purpose of the framework, in order to ensure the interconnectivity desired for the IAF.

The logic for connecting the components is to investigate the selected standards and guidelines in a parallel manner, then identify commonalities across them that enable the application of the IAF to the civil infrastructure systems.

3.1 Levels of the IAF: Domains, Subdomains, Standards and Guidelines

The IAF is based on four domains (the Level-1 of the framework):

- Enterprise Management Systems
- Enterprise Architecture
- Information and Knowledge Management
- Engineering Systems and Models

Under these domains, a set of Level-2 subdomains were selected, and subsequently selected relevant Level-3 standards and guidelines (standards, bodies of knowledge, best-practice) were identified. Only the elements of these standards most pertinent to the purpose of the IAF are considered, also with special emphasis on their commonalities and alignment across subdomains.

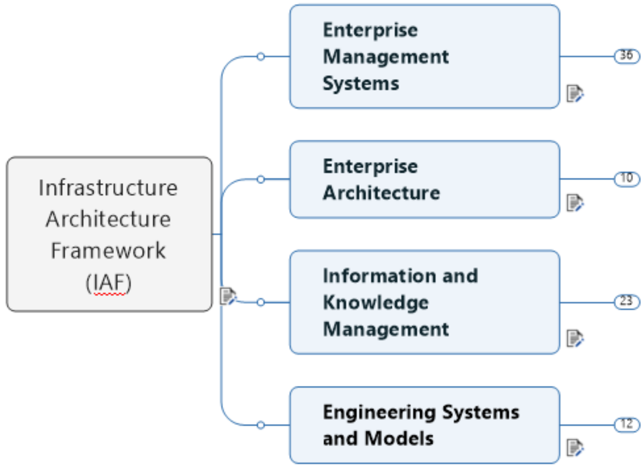

Figure 3-1: Infrastructure Architecture Framework

3.1.1 Level 1 – Domains

Domains are the primary category of the IAF and its specifications. Aligned with the proposal and mission of the project, they represent international best-practice for engineering, management, and information technology. They are listed as: Enterprise Management Systems, Enterprise Architecture, Information and Knowledge Management, and Engineering Systems and Models.

3.1.2 Level 2 – Subdomains

The subdomains of each discipline establish uniform engineering/technical criteria, methods, or processes. Each subdomain is broken down into the standards and guidelines that are relevant to the specifications for the IAF. For instance, ISO 55000 (Asset management — Overview, Principles, and Terminology) is considered under the subdomain Asset Management and TOGAF (the Open Group Architecture Framework) is considered under the subdomain Enterprise Architecture.

3.1.3 Level 3 – Standards and Guidelines

A group of standards, best-practices, and/or bodies of knowledge that comprise each of the subdomains, providing specific structure to the overall IAF. For example, the subdomain Systems Engineering and

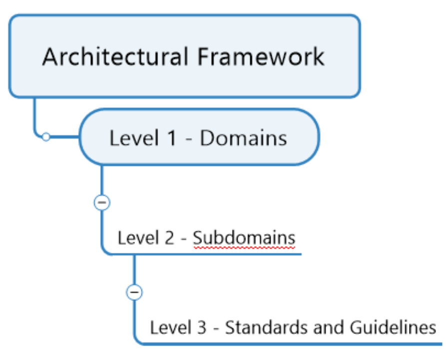

Figure 3-2: Architecture Concept Hierarchy

its body of knowledge[22], the INCOSE Systems Engineering Handbook, provides the content on holistic systems thinking techniques and modeling approaches. These standards and guidelines are connected across the four domains to accomplish the project's intent of "integration and amplification of existing professional standards" and "interconnections needed to support the overall system of systems."

Based on the Level-1 domains, extensive research helped identify standards and guidelines in line with the goals of the project.

The IAF provides structure for the work ahead, a conceptual model for the intellectual and organizing efforts in the design and deployment of the infrastructure system, and the "in-scope" or boundaries to contain and minimize its complexity and ambiguity.

For successful application to the civil infrastructure landscape of New York, the logic for connecting the IAF components was to investigate the selected standards and guidelines in parallel, to then identify commonalities across them. In this process, the project team kept fidelity to the mission and purpose of this program.

3.2 IAF Standards and Guidelines

3.2.1 Enterprise Management Systems

With the first domain, Enterprise Management Systems, the IAF defines relevant practices for the management of systems in asset-intensive civil infrastructure enterprises. A commitment to the lifecycle management of operations and maintenance, along with capital program delivery, drives the structure of this domain.

Community Context, Policy, Objectives

This subdomain offers practices that demonstrate and communicate stakeholder requirements responsibility and overall system performance, to help communities such as New York become more resilient, smart, and sustainable.

[22] The INCOSE SE Handbook is different to the Systems Engineering Body of Knowledge (SEBoK: SEBoK (sebokwiki.org)). The Handbook describes key processes performed by Systems Engineers. The SEBoK is much more comprehensive and suggest this is the body of knowledge.

The standards considered in this subdomain of the IAF are:

- *ISO/TC 268 Sustainable Cities and Communities* includes requirements, frameworks, guidance, and supporting tools related to achieving sustainable development, “smartness”, and resilience. The goal is the development and implementation of holistic and integrated approaches. Some of the chapters in this standard cover management systems, global city indicators, infrastructure metrics, integration frameworks, data exchange, and sharing (metadata, reference data, thematic data), a maturity model for assessment and indicators for city services and quality of life.
- *ISO/TC 268/SC 1 Smart Community Infrastructures* standardizes the technical aspects of smart infrastructures described in terms of scalable and integrated systems. It provides harmonized metrics for benchmarking and specifications in measurement, reporting, and verification of smart communities. Metrics examples are societal (secure, safe), economic (management efficiency), and environmental (natural resources), and they are to be applied at different stages in the lifecycle of community infrastructures (energy, water, transportation).
- *ISO 22370 Security and Resilience – Urban Resilience* is the standard providing the principles and framework (as a set of metrics and models) to structure urban resilience. Principle 2 of ISO 22370 is to employ a Systemic Approach to enable coherent monitoring of urban resilience development through indicators. It also proposes documenting the theoretical and rational framework, with a process methodology, tools, and techniques for urban resilience planning.
- *ISO 37101 Sustainable Development in Communities — Management System for Sustainable Development* provides a holistic approach for establishing requirements for a management system for sustainable development in communities such as cities. Relevant aspects of ISO 37107 are a vision for the city, supplier management, city data, digital, and physical resource management, integration of physical and digital assets, and management of data assets.
- *IEEE P2784 Smart Cities Planning and Technology* is the guide for a technology and process framework for planning a smart city, with a strong recommendation on the use of the internet of things to ensure interoperable, agile, and scalable solutions that can be maintained in a sustainable manner.

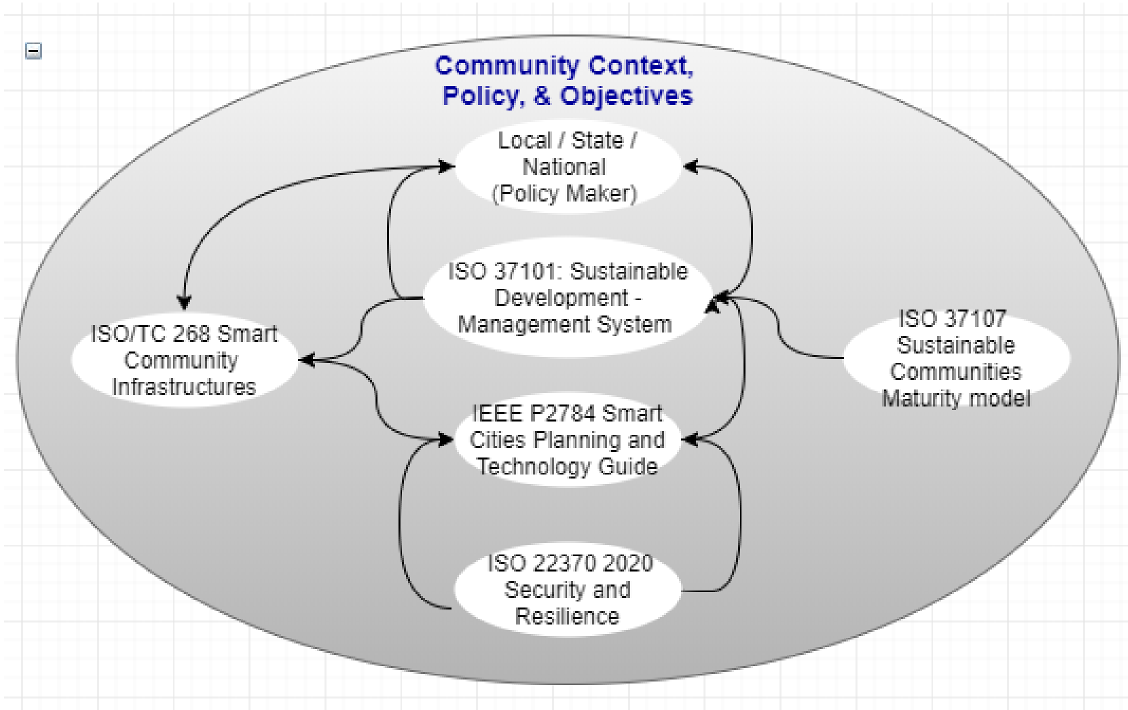

Figure 3-3: Community Context, Policy, Objectives

These standards and guidelines ensure the foundation for the IAF to become cohesive across domains. They share a similar approach with many other IAF components such as:

- Performance Management, Asset Management, Lifecycle Delivery, and *ISO 15926 Lifecycle Integration of Process Data*
- Data Interoperability Requirements under the T*OGAF Phase C Information Systems Architecture and Data Architecture*, as well as Reference and Master Data
- Requirements Management included across different domains of the IAF
- ArchiMate[23], MBSE[24], and Business Process Management as practices to model vision and motivation
- Internet of Things and Cybersecurity for the safety of individuals in the cities
- *ISO 44001* for Collaborative Business Relationship

Enterprise Planning, Management and Controls

This subdomain provides the IAF with the guidelines and high-level considerations to ensure proper planning and management of the enterprise, or primary "entity" setting the direction, monitoring, and resource allocation to achieve goals and objectives at the strategic level to deliver the systems requirements.

[23] ArchiMate® specification is a standard of The Open Group and an open and independent modeling language for Enterprise Architecture supported by different vendors. It provides instruments to enable Enterprise Architects to describe, analyze and visualize the relationships among domains https://www.opengroup.org/archimate-forum/archimate-overview

[24] MBSE: Model-Based System Engineering https://www.incose.org/docs/default-source/delaware-valley/mbse-overview-incose-30-july-2015.pdf

- Stakeholder Engagement. The Community Context, Policy and Objectives subdomain stresses inclusive stakeholder engagement and integrated planning to manage efficiently, maximize synergies, and minimize sector silos
- Governance and Compliance. ISO 55000 establishes the requirements for the governance of a risk-based asset management system and helps understand how performance, risk, and compliance fit in with the management of asset intensive infrastructure systems. Because of the common high-level structure ISO management standards like ISO 55000 enables effective alignment, integration, and continuous improvement of the enterprise strategies, plans, and operations across subdomains such as quality, asset management, information technology, risk etc.
- Performance Management. Operational Excellence is a framework for developing and executing a business strategy. Drawing from continuous improvement and other tools to align people, processes, and technology creating more value for stakeholders through performance management

(Note that the components Stakeholder Engagement, Governance and Compliance, and Performance Management are high-level notions, embedded throughout the framework and considered in many of its different standards and guidelines. They are included in this subdomain "Enterprise Planning and Management" as they pertain mainly to the control and management of the enterprise).

- *ISO 9000 Standards* effectively document quality management, particularly ISO 9001, which sets out the requirements for a quality management system (QMS), based on seven principles:
  - Customer focus (requirements, alignment of objectives with customer needs)
  - Leadership (vision, direction, modeling of organizational values, employee empowerment)
  - Engagement of people (skills, ownership, performance, knowledge)
  - A process approach (measured, connected, improved)
  - Improvement (performance, capabilities)
  - Evidence-based decision making (data quality)
  - Relationship management (suppliers, partners, supply chain)
- *ISO 31000 Risk Management - Principles and Guidelines* defines the process to integrate risk management into governance, integrating policies, procedures, and practices under the following sequence of activities: establish management context and criteria, risk assessment, identification, analysis, evaluation, treatment, communication, and monitoring / reporting. Risk management is aligned with performance, quality, and asset management through a common high-level structure

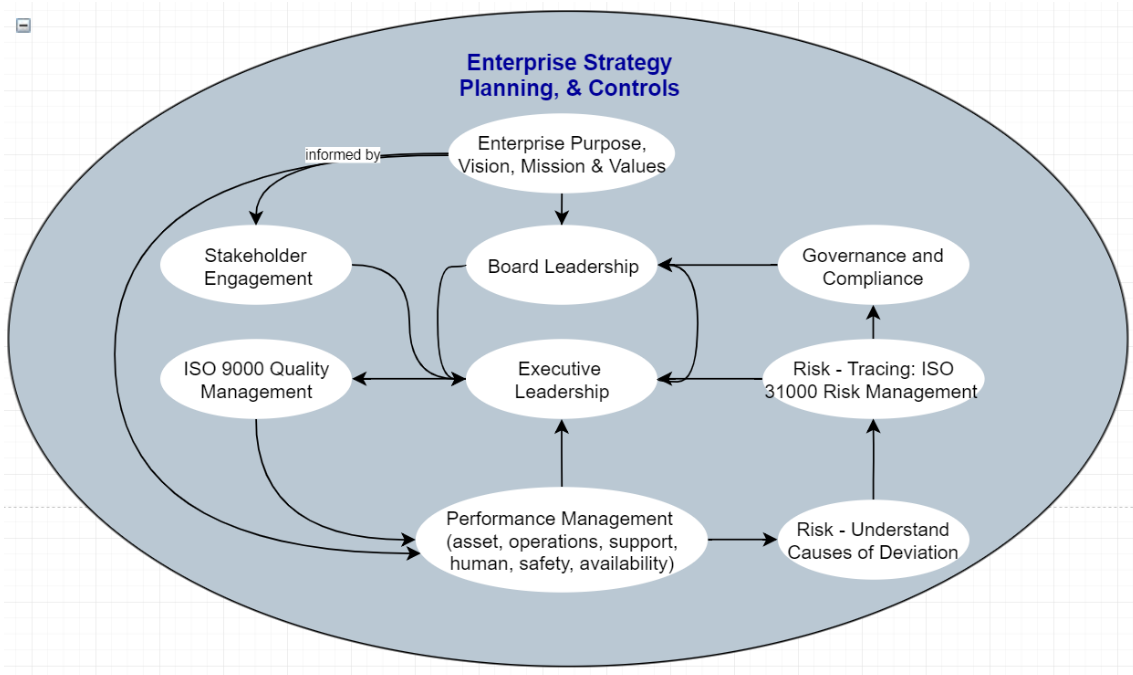

Figure 3-4: Enterprise Strategic Planning, Management and Controls

Enterprise Planning, Management and Controls assists in documenting and maintaining the quality system of the IAF. It ties with IAF components such as:

- Asset management and capabilities (decision-making, organization, risk)
- ISO 55000 management systems
- Organizational change management
- ArchiMate as modeling technique of organizational values, vision, motivations, and leadership
- Supply chain management for the administration of relationships

Asset Management, Capabilities, Operations and Controls Systems

Asset management is a foundational subdomain of the IAF providing global standards for the management of physical assets. The IAF follows structural guidance from two guidelines: the *British Standard Institute ISO 55000 Series 2014 Asset Management (principles, management systems requirements, application)*, and guidelines developed by the Institute of Asset Management (IAM[25]). These guidelines allow the target enterprise of the IAF to align efforts under a comprehensive asset management system, maximizing ROI from assets, and the overall lifecycle of the infrastructure as a system. The IAF includes the major aspects of *ISO 55000* around organizational strategy, policy, governance, and project delivery.

- *ISO 55000* aligns with the IAF Enterprise Architecture domain and its *TOGAF Phase A* (Architecture Vision) that captures policy development and strategic decisions (such as an asset management policy). *TOGAF Phase A* has the goal to develop a high-level

[25] IAM: The Institute of Asset Management https://theiam.org/

aspirational vision of the capabilities of the enterprise. Particularly, *TOGAF Phase A* step 6.3.8 focuses on developing the architecture vision and its key elements: enterprise mission, vision, strategy, and goals, in line with the IAF Purpose.

The high-level PDCA (Plan, Do, Check, Act) iterative design and management method is the original basis for the formulation of *ISO 55000*, which is underpinned by two of the six pillars of the Institute of Asset Management (IAM) Conceptual Model:

Figure 3-5: Asset Management, Capabilities, Operations & Control Systems

- Asset Management Strategy and Planning, including key aspects such as investment planning and budget management along with the total cost of expenditure (ToTEx[26], as Capital Expenditure and Operational Expenditure) and where budget is considered as the driver for the enterprise and not just part of the enterprise. The IAF also includes an activity-based costing (ABC[27]) framework and the relationship of the asset register to the financial register. The IAF follows guidance on optimization of lifecycle costing from:
  - *ISO 15686-5:2017 Buildings and Constructed Assets* — Service Life Planning — Part 5: Life-Cycle Costing
  - Guidance from the Royal Institution of Chartered Surveyors provided in *RICS[28] UK Life cycle costing*
- Asset Information to ensure effective asset data management throughout the lifecycle for asset delivery, especially in the relationship between CapEx, OpEx, asset service data, and asset engineering data. Here, the IAF leverages best-practice standards and guidelines from:
  - ISO 10007:2017 Quality Management — Guidelines for Configuration Management to establish and rigorously maintain asset configuration data, strategically important to the enterprise, from the very beginning of the asset lifecycle
  - BIM (Building Information Modeling) and ISO 19650 to exploit technology advances such as 3D models as a tool to manage construction fit-out and to link to asset data through the geographical information system (GIS)

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[26] Total Expenditure = Capital Expenditure (CapEx) + Operational Expenditure (OpEx)

[27] ABC (Activity-based costing). Industrial and Management Systems Engineering: Combining Activity-Based Costing with the Simulation of a Cellular Manufacturing System https://core.ac.uk/download/pdf/188058417.pdf

[28] RICS (Royal Institution of Chartered Surveyors) professional guidance, UK Life cycle costing https://www.rics.org/globalassets/rics-website/media/upholding-professional-standards/sector-standards/construction/black-book/life-cycle-costing-1st-edition-rics.pdf

- Additionally, the IAF considers the proper definition of asset breakdown structures (ABS) aligned with project work breakdown structures (WBS) and cost breakdown structures (CBS) to enable better visibility, more progress, and better structured outcomes. These structures are supported by asset identification standards, asset data dictionaries, and master configuration baselines

The other 4 pillars of the IAM Conceptual Model are:

- Asset management decision-making, to maximize value from operating assets
- Asset management lifecycle delivery, which implements the asset management plan from the Asset Management Strategy and Planning pillar and focuses on the integration of activities across the asset lifecycle
- Organization and people, connected to the IAF subdomain “Organizational Change Management”, and provides guidance on change and leading the enterprise to question traditional ways of thinking and working
- Risk and review, linked to the IAF components “Risk Management”, “Performance Management”, and “Business Intelligence”, and which contains core activities associated with the identification, understanding, and management of risk

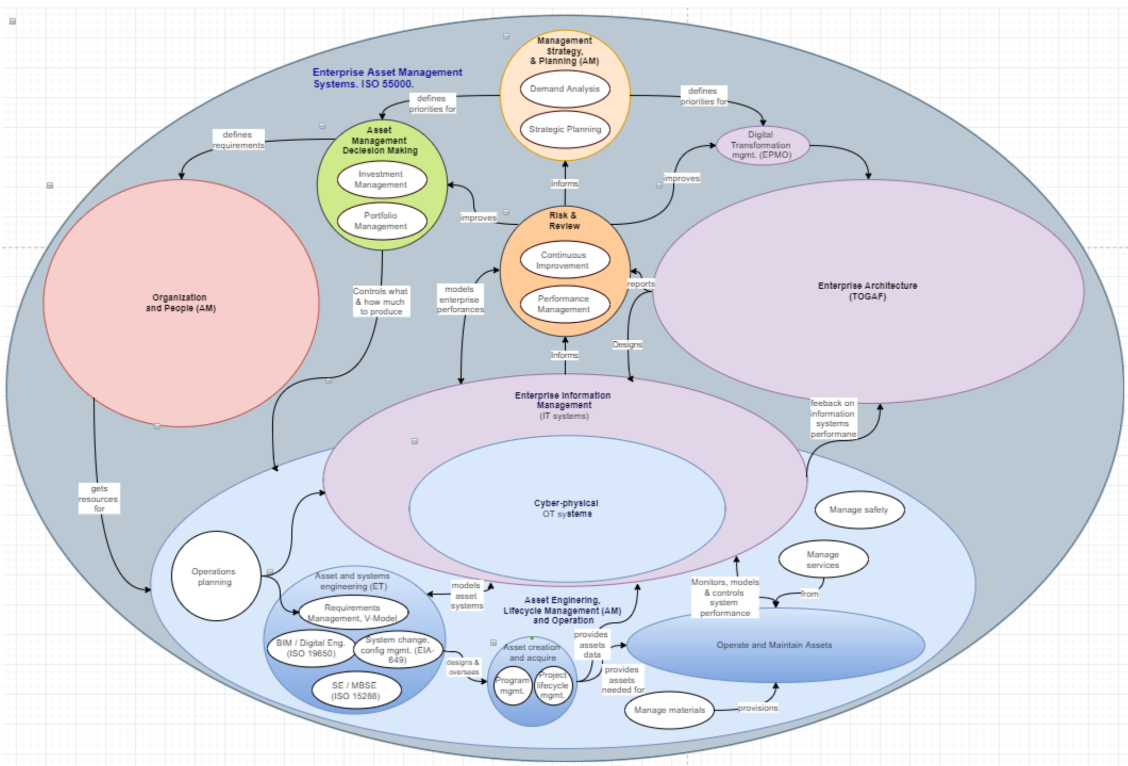


Figure 3-6: Enterprise Asset Management Systems

The IAF is a framework for the management of physical assets and infrastructure, the subdomain “Asset Management” is connected to, and influences all aspects and components of the IAF. Asset management, as the operations and activity of the enterprise, provides the content of the IAF, whereas the business architecture is the channel for distributing this content, making sure asset management integrates with other components of the IAF. Technically, this can manifest as the 6-box IAM conceptual model breaking down into the best-practice from infrastructure operator New York Metropolitan Transportation Authority (MTA), and its MTA Business Architecture or Business Capabilities Model (BCM[29]): a level 1 of business functions and subjacent business capabilities.

According to the Institute for Asset Management core publication *IAM Anatomy*, Section 6.3.3., the IAM Conceptual Model aligns with the other IAF components "V-Model" (covered above), and Configuration Control and Management (covered under Section 5.x below). IAM capabilities model also aligns with the IAF Enterprise Architecture domain and its *TOGAF Phase B* Business Architecture, the blueprint of the enterprise providing governance and common understanding of capabilities and processes.

Portfolio, Program and Project Management

The Program Management subdomain of the IAF, as the process of coordinating large and complex civil infrastructure and construction systems, relies on best-practice guidelines:

- *Managing Successful Programs (MSP)*
- supported by *Portfolio-Program-Project Office (P3O)*
- the *Project Management Body of Knowledge (PMBoK)*
- and *Prince2* (Projects in a Controlled Environment).

MSP defines a process for the delivery of transformational change through the application of program management. Leveraged worldwide, MSP also addresses proper governance, leadership, planning and control, risk management, and quality management.

The MSP blueprint arguably maps to a combination of the *TOGAF* statement of architecture work and the architecture requirements specification. This MSP approach of mapping outcomes to benefits has clear analogues to the *ArchiMate* motivational[30] elements. (*ArchiMate* is a widely used notation and language to describe Enterprise Architectures). Thus, a useful relationship between Enterprise Architecture and Program Management is established for the application of the IAF.

Regarding the project delivery component of ISO 55000, the IAF also includes the systems engineering subdomain with its ISO 15288:2015 Systems Engineering - System Lifecycle Processes. This standard establishes a common framework of process descriptions for describing the lifecycle of asset systems and the "V-Model" for project and asset lifecycle traceability.

Best-practice work performed in the enterprise architecture community shows that *ArchiMate* and *TOGAF* can be successfully integrated with other frameworks such as *PMBoK* and *MSP*, thus confirming for IAF purposes the close interface between Enterprise Architecture and Program Management. The *TOGAF* Architecture Development Method cycle focuses on

29 Building an Asset Management System ▪ Part 1: The Business Architecture of the MTA Metropolitan Transportation Authority https://www.linkedin.com/pulse/building-asset-management-system-business-carlos-maestre/

30 Motivation concepts are used to model the reasons that influence, guide and constrain the design or change of the enterprise's architecture. They are represented by goals, stakeholders, drivers/conditions, assessments, outcomes, principles, requirements, constraints, meanings, values.

Enterprise Architecture transformation, while MSP concentrates on governance and stakeholder management.

The enterprise vision can be modeled into Blueprints that are then developed into Program Plans. Enterprise architects analyze the program management of the enterprise in order to define implementation projects. To support this exercise, the MSP Blueprint considers change from four angles: People, Organization, Technology, Information, referenced as “POTI.” The POTI Model sets a high-level scope of what must be included and integrated in an effective Blueprint: processes and organization (business architecture, business capabilities, business processes, organizational models) along with technology and information (information architecture, data relationships, reporting).

Prince2 supports MSP as a project management method guiding the enterprise through the essentials for managing successful projects, built upon seven themes: Business case, Organization, Quality, Plans, Risk, Change, and Progress.

Finally, *P3O* provides a delivery support/control structure for change initiatives within an organization. It helps to deliver business objectives and realize business outcomes. It provides a center of excellence for the organization, including the setting and monitoring of standards.

Legal and Procurement Framework for Enterprise Innovation

With regards to contractual and legal aspects of the civil infrastructure space, the IAF considers the following two bodies of knowledge:

First, the International Federation of Consulting Engineers (FIDIC) family of Contract Templates, which provide standard form conditions of contract for the construction industry. FIDIC contracts represent agreements and standard contracts for a variety of construction and installation projects. The FIDIC *Red Book* (conditions of contract for construction for building and engineering works designed by the employer) and the FIDIC *Yellow Book* (Design & Build conditions) are the most commonly used when most or all of the assets are designed by (or on behalf of) the employer or owner.

Secondly, the *Institution of Civil Engineers Project13* (*ICE P13*) program sets out a delivery model based on collaboration between client organizations (owners) and contractors. Project13 advocates for an “Enterprise” model, creating a long-term relationship between owners, investors, integrators, advisers, and suppliers with an integrated team commercially incentivized to deliver better outcomes. This results in a more optimal organizational collaboration, with the asset owner defining their requirements (driven by operational not project workflows), so that all players in the civil infrastructure supply chain understand blueprints and project execution.

This subdomain is linked to components of the IAF such as lifecycle delivery (included under Asset Management), budgeting, organizational change management, requirements management, digital engineering, and supply chain management, with all the techniques and tools included in each of these.

Additionally, under the IAF domain Enterprise Architecture, *TOGAF*, and the *ArchiMate* notation describer a business layer concept. This business layer includes elements describing the provision of services. It has active structure elements (entities that constitute the organization such as business actors) and passive structure elements (business objects such as products and contracts, manipulated by behavior). *ArchiMate* considers a contract as a "formal or informal specification of agreement that specifies the rights and obligations associated with a product or service." Therefore, the Legal and Procurement subdomain connects with and is supported by *TOGAF* and the Enterprise Architecture subdomain of the IAF, for the purpose of modeling contracts.

Supply Chain Management (SCM)

The *Supply Chain Operations Reference Model* (SCOR), of the Supply Chain Council (SCC), is the cross-industry standard for supply chain management, a management tool, and a process reference model. It describes the business activities associated with all phases of users' demands.

The SCOR methodology assumes that all supply chain processes can be subdivided into one of five general process types (Plan, Source, Make, Deliver, and Return), that define the scope and content for the supply chain strategy, inputs/outputs, and performance metrics.

The operations in range of the SCOR model are supplier-customer interactions, physical material transactions, and market interactions.

SCOR includes the following levels:

- Level 1 process types: plan, source, make, deliver, and return
- Level 2 process categories: regarding configuration of the supply chain by the enterprise (planning, execution, enablement)
- Level 3 or process element level: detailed process element information for each level 2 process category is presented and the process performance metrics are defined

With regards to performance:

- m0 measures (organization metrics) for measuring the enterprise performance impact on the overall effectiveness of the supply chain
- m1 measures (supply chain metrics) for measuring the overall performance of the civil infrastructure supply chain

Organizational Change Management (OCM)

The Infrastructure Architecture Framework includes a subdomain on change management, people management, and organizational behavior of the enterprise. It embraces relevant standards and best practice such as:

The Association of Change Management Professionals (ACMP) Standard for Change Management. This standard establishes change management areas (or process groups) and a change process including an initial evaluation of change impact and organizational readiness (change, vision, stakeholders, risk assessment) followed by a formulation of the change management strategy (leadership, organization, and process design, performance management, sustainability) in order to develop and execute a change management plan.

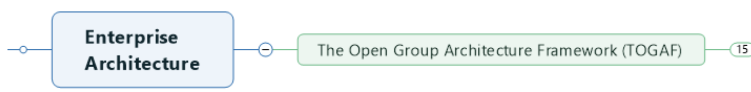
The Prosci ADKAR[31] *Change Management Model.* This model provides the tools and information required to get stakeholders through change successfully with the following phases:

- Awareness of the concrete need for change management
- Desire to participate in the application of change management, making the case for it
- Knowledge about how to apply change management, with training as the key mechanism
- Fostering the ability to implement new skills and behaviors, by providing hands-on instruction, one-on-one coaching, access to subject matter experts, or two-way communication
- Reinforcement to sustain the management of change, by engaging senior leaders and providing frequent sponsorship and endorsement in projects, including progress monitoring

According to Giachetti, enterprise architecture describes “the structure of an enterprise. Its decomposition into subsystems, the relationship between the subsystems, the relationship with the external environment, the terminally to use and the guiding principles for the design and evolution of an enterprise”

3.2.2 Enterprise Architecture

Enterprise Architecture (EA) is a high-level design or blueprint of an entire system and/or enterprise.32 It provides a language for describing the structure of an enterprise, its businesses processes, how they are coordinated with each other and the technology that supports them. EA often produces a blueprint that aligns the system’s capabilities, processes, information, and knowledge models, enabling the enterprise analysis, design, planning, and implementation for the development and execution of strategies.



TOGAF (The Open Group Architecture Framework)[33], along with its *Architecture Development Method (ADM)* manifestation, is a standard methodology for assisting in the acceptance, production, use, and maintenance of Enterprise Architecture. It considers the enterprise as a system and aims for a balance between promoting the concepts of *ISO/IEC 42010:2007* and retaining other commonly accepted terminology.

The IAF uses the five of the *TOGAF* phases, along with *ArchiMate* and Business Process Management (BPM):

- *TOGAF Phase A* (Architecture Vision) develops a high-level aspirational vision of the capabilities and value to be delivered by the IAF and captures policy development and strategic decisions (e.g., asset management policy) to enable subsequent work, connecting with *ISO 55000* and “Strategy & Planning” under the subdomain Asset Management and Capabilities

[31] The Prosci ADKAR (Awareness, Desire, Knowledge, Ability, Reinforcement) Model https://www.prosci.com/methodology/adkar

[32] Giachetti, R. E. 2010. "Design of Enterprise Systems: Theory, Architecture and Methods." CRC Press.

[33] TOGAF | The Open Group Website

- *TOGAF Phase B* (Business Architecture) is the blueprint of the enterprise, providing governance, and a common understanding of the IAF capabilities and business processes and is used to align strategic objectives and tactical demands
- *TOGAF Phase C* (Information Systems Architecture and Data Architecture) describes the structure of the enterprise's logical and physical data assets and data management resources and develops the systems architecture that enables the business architecture and the architecture vision while addressing stakeholder concerns
  - TOGAF Phase C also has multiple data management guidelines that link to the "Data, Information and Knowledge Modeling" subdomain
  - *ISO IEEE 42010 Systems and Software Engineering Architectural Description* standard (evolved from *IEEE 1471 Description of Software Intensive Systems Architectures*) helps establish, describe, analyze, and sustain architecture views in systems (information systems, systems-of-systems) where software plays a substantial role. *ISO IEEE 42010* connects with *TOGAF Phase C: Information Systems Architecture*, as it helps describe how information systems enable the business architecture and the architecture vision for both data and applications
- *TOGAF Phase H* (Architecture Change Management) establishes an architecture change management process and ensures that the architecture lifecycle is maintained, the architecture governance framework is executed, and the enterprise architecture meets requirements
- TOGAF *Phase Requirements Management* defines a process whereby requirements for the enterprise architecture are identified, stored, and fed into other IAF components
- *ArchiMate* is the recommended modeling language to describe the enterprise IAF architecture and its vision, aspirations, motivations, outcomes, and drivers and it is capable of integration with ITIL[34], Prince2, and MSP
- The practice of *Business Process Management (BPM)*. The enterprise is able to gather massive amounts of event data that is generated as major business processes are executed. The resulting data from transactions, databases, social media, etc. is stored in different data formats

As described under the Asset Management subdomain, the IAF incorporates asset management (providing the content) into the business architecture (the channel for distributing that content), making sure asset management integrates with other components of the IAF.

Plan-Do-Check-Act (PDCA) Quality process is the original basis for the formulation of *ISO 55000*, which is underpinned by the *IAM Asset Management Conceptual Model* and its business functions and capabilities which define a business architecture. An additional input to *TOGAF Phase B* is the Communications Plan.

It establishes a conceptual framework for describing architecture views and for the creation, analysis, and sustainment of systems' architectures.

TOGAF embraces *ISO/IEC 42010:2007* terminology, which defines "Architecture" in the context of *TOGAF* as "the fundamental organization of a system, embodied in its components, their

[34] The Information Technology Infrastructure Library (ITIL)

relationships to each other, the environment and the principles governing its design and evolution".

ISO 42010 also introduces the notion of architecture views. TOGAF embraces and encourages the concepts in *ISO 42010*, specifically those that help guide the development of an architecture viewpoint and make it actionable. These concepts can be summarized as the selection of key stakeholders and the documentation (modeling) of their concerns.

In summary, Enterprise Architecture is certainly essential to most aspects of the IAF and to engage in systems thinking. More concretely, Enterprise Strategic Planning, Asset Management, Program Management, Organizational Change Management, Collaborative Information Sharing, Data, Systems Engineering, and Modeling.

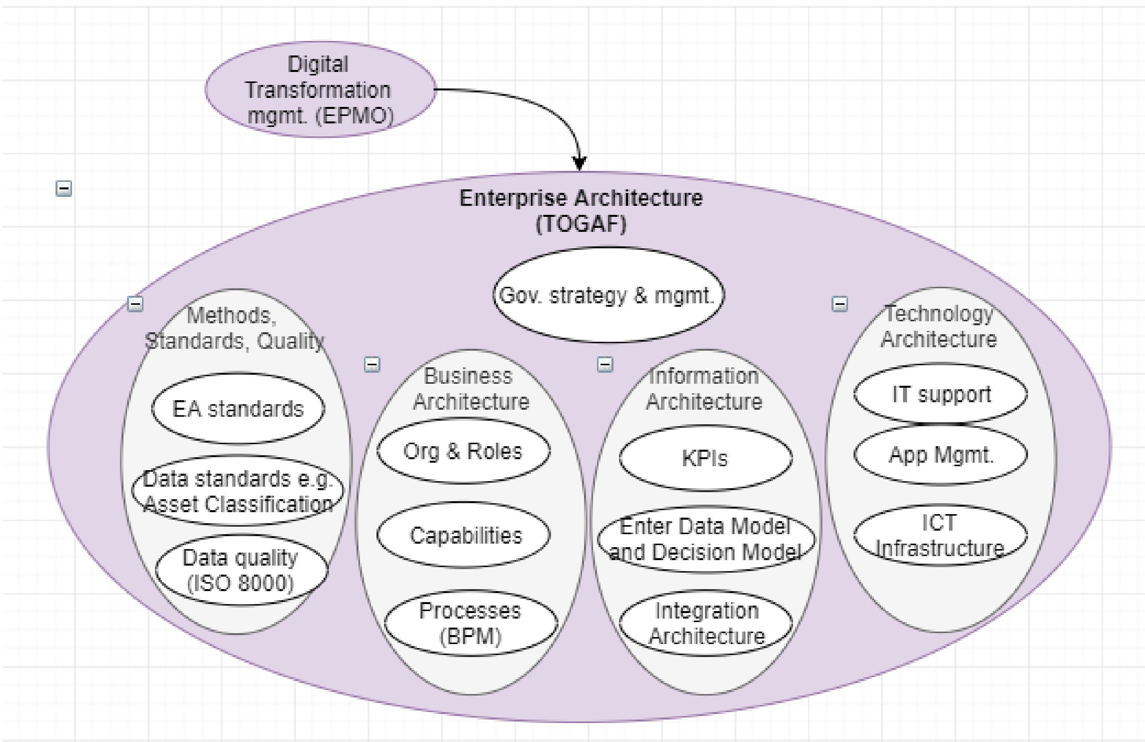
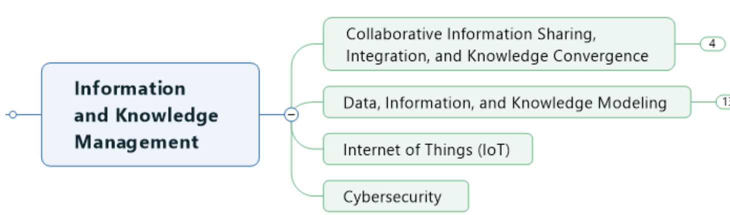


Figure 3-7: Enterprise Architecture Management

3.2.3 Enterprise Information and Knowledge Management

This domain provides the IAF with a platform where the evolution and information and knowledge of the framework can be shared and monitored. The goal is to share data efficiently, with a single approach to reference data and where components such as cybersecurity, IoT (Internet of Things), interoperability, and data integration can be hosted.



Following guidance and lessons learned from our experts, a collaborative information sharing infrastructure is critical. One of the IAF advisors from the UK, framed it this way:

> "To share data efficiently, a single approach must be taken across the built and natural environment to ensure data is consistent. This means use of a common data model and reference data, as the core of a Digital Framework at the heart of Digital Built Britain. What is required now is to establish a programme to develop the Digital Framework as a public good, together with a number of pilot projects to demonstrate the benefits of its adoption."

Collaborative Information Sharing, Integration and Knowledge Convergence

The IAF considers four standards/practice areas for collaborative information sharing:

- *ISO 30401 Knowledge Management:* The purpose of knowledge management is the selection of the appropriate knowledge to inform better decision-making. It has statistical processes for discovering, generating, and updating knowledge from data and information, with the goal of educating a competent and capable asset owner on the value of data and models for end users, and generate an ecosystem of asset governance and data discipline
- *ISO 44001 Collaborative Business Relationship* (formerly BS 11000):
  This standard is the tool and practice to help the enterprise implement a system of establishing and managing collaborative relationships across the supply chain. The core concepts are context of the enterprise, issues that affect the enterprise, stakeholder needs, and expectations, leadership requirements, risks, communication requirements, nonconformities, and corrective actions, and performance evaluation and measurement of the collaboration management system
- *Skills and Competency Framework (CDBB)*[35]*:* This framework sets out requirements for different roles in the architecture, engineering, and construction industry (cybersecurity specialist, data architect, process modeler, business analyst, change manager, enterprise architect) with the skills to realize the digital transformation of the built environment. The framework emphasizes the need for a culture shift towards improving data quality and adopting the systems-based outcomes-focused approach that the IAF promotes. This OCM subdomain is related to other IAF subdomains and underlying standards and guidelines such as *ISO 9001* quality management, BPM (process) and *ArchiMate* under enterprise architecture: performance management and business intelligence: cybersecurity; data; digital engineering; systems engineering[36]; risk management; sustainability; training, education, and guidance
- *Training, Education, Guidance*: lastly, the IAF will combine the standards and guidelines under this subdomain to generate the empowerment of individuals involved

The Collaborative Information Sharing subdomain of the IAF connects with enterprise strategic planning (risk management, performance management), asset management decision-making,

35 New framework highlights new career opportunities being created by the National Digital Twin | Centre for Digital Built Britain)

36 INCOSE Systems Engineering Competency Framework for Systems Engineering practitioners and its INCOSE Z6 Systems Engineering Competency Framework https://incoseuk.org/Documents/zGuides/Z6_Competency_july2020_issue1.1_pdf_web.pdf

supply chain management, organizational change management, systems engineering, digital engineering, and modeling.

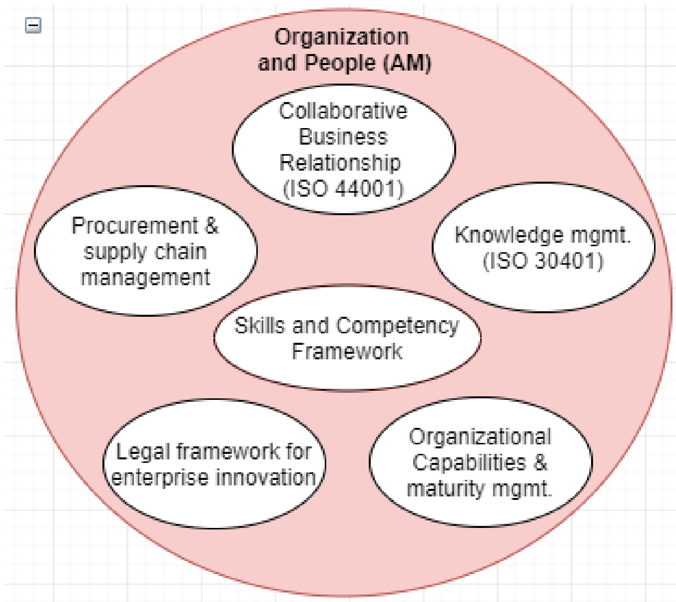


Figure 3-8: Organization and People

Data, Information, and Knowledge Modeling

The Data, Information, and Knowledge Modeling subdomain covers the interoperability and data architecture aspects of the Infrastructure Architecture Framework. An enterprise common data environment (CDE), a referenced central repository, and single source of information (documents, contracts, reports, bids, models).

Data ontologies will assist in specifying components such as individuals, classes, attributes, and relationships for a common understanding of different concepts. They will also enable modeling and allow the interoperability necessary for the effective application of the IAF.

The IAF leverages several recognized standards for this subdomain:

- ISO 15926 Industrial Automation Systems and Integration, Integration of Life-Cycle Data, Part 13 (Integrated Asset Planning Lifecycle). While originally developed as a standard for process plants it specifies an XML[37] schema for the exchange of data used for asset planning valuable in other asset-intensive contexts
- *ISO 8000 Data Quality and Enterprise Master Data.* This standard defines quality requirements on the exchange of data to support and measure business processes

Additionally, the following guidelines are included under this subdomain:

[37] XML Schema describes the structure or legal building blocks of an XML document

- *Information Management Framework (IMF).* Progress at the Centre for Digital Built Britain (in collaboration with the Construction Innovation Hub) in developing the IMF to enable secure and resilient data sharing across the built environment is a critical milestone towards a national digital twin. The IMF clarifies the way that digital twins are connected for ensuring the security and resilience of assets and systems. Its goal is to establish a common language by which digital twins of the built and natural environment can communicate securely and effectively to support improved decision-making. The IMF consists of:
  - *Foundation Data Model (FDM)* – consistent understanding of digital twins. An ontological model to describe general concepts, including collaboration with builders and sector experts for the relationships between digital twins, models, datasets, and physical twins
  - *Reference Data Library (RDL)* – the set of classes and properties to describe digital twins, including vocabularies (taxonomies) to standardize choices across sectors
  - *Integration Architecture (IA)* – the protocols enabling the managed sharing of data
- *Geographic Information System (GIS) and Spatial Intelligence.* This includes guidelines from the Open Geospatial Consortium (OGC) for the exchange of geospatial information
- *Master and Reference Data.* The IAF relies on the contextualization of data. *Master Data* describes places (locations, sites), parties (suppliers, asset owners, employees, clients), and things (materials, parts, vehicles), and is shared by the systems and processes of the enterprise. *Reference Data* is the set of permissible data to be used from the Master Data for classification by other data fields and that clarifies the interpretation of a data record
- *Business Intelligence and analytics.* Business intelligence (BI) refers to the procedural and technical infrastructure that collects, stores, and analyzes the data produced by a company's activities. Business Analytics refers to the skills, technologies, and practices for continuous iterative exploration and investigation of past business performance to gain insight and drive business planning. BI and analysis tools and models are essential for converting data (including social media data) into knowledge and decision-making. Business Intelligence standards provide guidance to agencies on the current standards and the status of other BI solutions that are being used or being considered for use. The IAF follows business intelligence guidelines by The Open Group [38] aligned with data management, data warehousing, and The Open Group TOGAF

Internet of Things (IoT)

Internet of Things is a subdomain under Enterprise Information and Knowledge Management considered pertinent to the purpose and approach of the IAF and in particular to asset management.

More specifically, IEEE P2413 Standard for an Architectural Framework for the Internet of Things (IoT), which also conforms to the international standard ISO/IEC/IEEE 42010:2011, addresses concerns shared by IoT system stakeholders across multiple sectors (e.g.,

38 The Open Group and DMBoK (Data Management Body of Knowledge) - Digital Practitioner Body of Knowledge™ Standard https://pubs.opengroup.org/dpbok/standard/chap-ent-info-mgmt.html#_data_warehousing_and_business_intelligence

transportation, smart grid) about building a connected community that can interoperate while meeting both the needs of enterprises and society. IEEE P2413 is for vendors, buyers, and system designers to accelerate the design, implementation, and deployment of such systems.

The purpose of the standard is to promote cross-domain interaction, aid system interoperability, and reduce industry fragmentation.

IoT standard IEEE 2413 provides:

- A reference model defining relationships among various sectors
- A reference architecture defining basic architectural building blocks to be integrated in multi-tiered systems
- A blueprint for data abstraction and data trust that includes protection, security, privacy, and safety

The massive amounts of data generated by both IoT and IIoT (Industrial internet of things) represent a tremendous opportunity for forward-thinking and asset-intensive enterprises to design more efficiently, construct, commission, operate, maintain, decommission, and replace physical assets. The IoT subdomain of the IAF therefore connects with community context, asset management (lifecycle), enterprise architecture, collaborative information sharing, data, and systems engineering.

Cybersecurity

Cybersecurity in the operation and management of a data-driven urban infrastructure is another subdomain of the IAF. As the practice of protecting architectures, systems, or networks from digital attacks, cybersecurity is represented by the National Institute of Standards and Technology (NIST) standard document *Framework for Improving Critical Infrastructure Cybersecurity* which provides guidance for physical asset owners on updating their information management and identifying and detecting cyber threats to their urban infrastructure systems.

Cybersecurity and the NIST standard are considered to be integrated into all four domains of the IAF. In addition, cybersecurity can be viewed as a system engineering process that allows the enterprise to continuously update information management in order to detect and identify cyberthreats.

The NIST Framework is a risk-based approach composed of three parts:

- Framework core functions
- Framework implementation tiers
- Framework profiles

The framework core consists of five concurrent and continuous functions that organize basic cybersecurity activities:

- Identify: develop organizational understanding to manage cybersecurity risk to systems, assets, data, and capabilities. Understanding business context, resources, and risks enabling the enterprise to focus and prioritize efforts. Examples of outcome categories within this function include asset management, governance, and risk management strategy

- Protect: implement safeguards to ensure delivery of critical infrastructure services, supporting the ability to contain the impact of a cybersecurity events
- Detect: activities to identify the occurrence of a cybersecurity event
- Respond: take action regarding a detected event
- Recover: maintain plans for resilience and to restore any capabilities or services that were impaired due to a cybersecurity event

The IAF also considers:

- NIST 800-53 (Security and Privacy Controls for Information Systems and Organizations), which defines risk management framework controls.
- NIST 800-160v2 (Developing Cyber Resilient Systems: A Systems Security Engineering Approach) that defines systems security engineering for IoT systems.

The cybersecurity area of the IAF is linked to community context (urban systems), asset management, risk management, data, and (as mentioned previously) systems engineering.

Data, Information and Knowledge Modeling components are spread throughout the IAF, especially under community context, asset management lifecycle, performance management, requirements management, business process management, cybersecurity, systems engineering, and modeling and digital engineering.

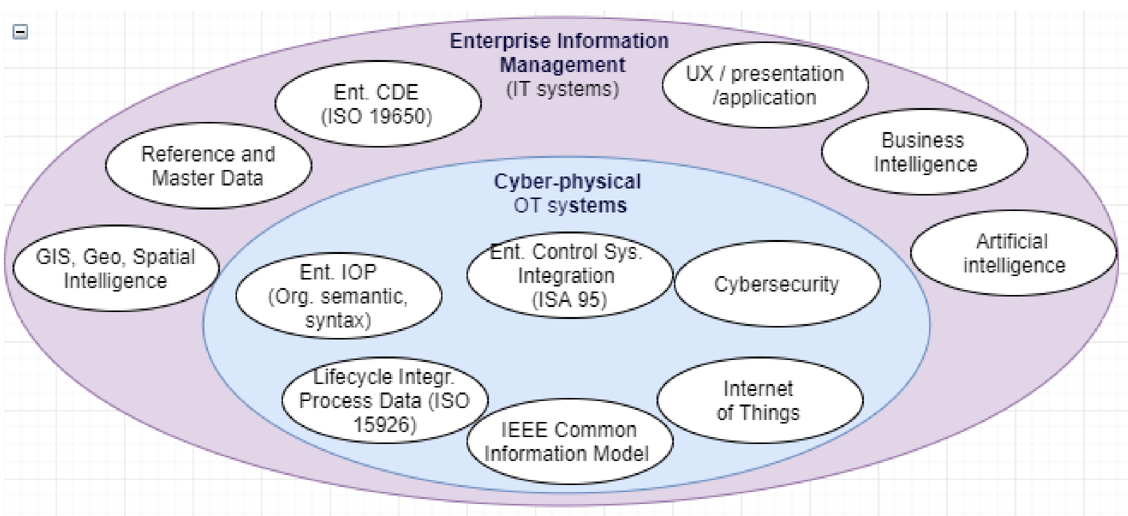


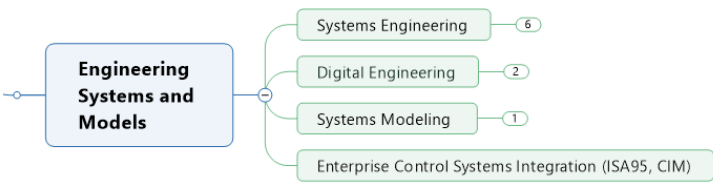
Figure 3-9: Enterprise Information Management

In addition, the IAF presents an essential connection between Data, Information and Knowledge Modeling, and the *Phase C: Information Systems Architectures and Data Architecture* component of the TOGAF subdomain under Enterprise Architecture. The components listed above are interrelated to the TOGAF Phase C components Validated Data Principles, Business Data Model, Logical Data Model, Data Management Process Models, Data Interoperability Requirements, Relevant Technical Requirements and Business Requirements.

3.2.4 Engineering Systems and Models

Systems Engineering

The IAF relies on the Systems Engineering subdomain as the approach to manage the technical and managerial activities that transform stakeholder needs and expectations into viable solutions for the target asset (system, or system of systems) throughout its lifecycle. Systems Engineering establishes a common framework, set of processes, and associated terminology for describing the lifecycle of systems.



The Hitchins-Kasser-Massie (HKF) Framework for Systems Engineering[39] supports the architecture modeling of civil infrastructure as multidimensional socio-technical systems over the systems lifecycle phases. The vertical dimension of the HKF five-layer framework form a "nesting" model. (i.e., a technical system (Layer 2) is made up of many assets or products (Layer 1); a business or enterprise (Layer 3) is made up of many systems; an industry supply chain (Layer 4) requires many businesses; and many industries make a socio-economic system (Layer 5).

Layer of Systems Engineering \ Phase in the Life Cycle		Needs identification	Requirements	Design	Construction	Unit testing	Integration & testing	O&M, upgrading	Disposal
Socio-economic	5								
Supply Chain	4								
Business	3								
System	2								
Product	1								
		A	B	C	D	E	F	G	H

The main system of interest of the IAF is Layer 3, the enterprise business system (e.g., infrastructure owner operator) responsible for managing the technical system lifecycle, (layer 2), the integration of assets (Layer 1), and its supply chain (layer 4) within the socio-economic context of its community service area (Layer 5). An example from our case studies would be a public or private infrastructure entity serving the New York region and its energy, water, utilities, or transportation requirements.

The Infrastructure Architecture Framework includes:

- I*NCOSE (International Council on Systems Engineering)*/ The IAF leverages the professional advice of INCOSE, the global professional society for the application of systems thinking and

[39] Kasser, J. E. (2007). A Framework for Understanding Systems Engineering. United Kingdom.

systems engineering and its handbook guide for the implementation of ISO 15288. *SEBoK* (systems engineering body of knowledge)

- *ISO/IEC/IEEE 15288:2015 Systems Engineering - System Lifecycle Processes.* This standard establishes a common framework of process descriptions for the lifecycle of systems and their associated terminology from an engineering viewpoint
- *V-Model* is a system lifecycle process model, that assists in the application of a systems engineering approach for managing contract and project requirements and in the asset lifecycle traceability for enhanced change management. It is also the recursive partitioning of the systems architecture, so that scopes and interfaces can be defined contractually and outsourced, to be delivered separately across the civil infrastructure supply chain. This architecture and partitioning enable individual parts, components and subassemblies involved in the built infrastructure to be fabricated and assembled separately by different firms
- IEC TS 62775 Application Guidelines – Technical and Financial Processes for Implementing Asset Management Systems. This standard maps ISO 55000 to ISO 15288
- ISO IEEE 42010 Systems and Software Engineering Architectural Description. This standard, evolved from IEEE 1471 Description of Software Intensive Systems Architectures, helps establish, describe, analyze, and sustain architecture views in systems (information systems, systems-of-systems) where software plays a substantial role. ISO IEEE 42010 connects with TOGAF Phase C: Information Systems Architecture, as it helps describe how information systems enable the business architecture and the architecture vision for both data and applications

  Figure 3-10: Hitchins-Kasser-Massie Framework for Systems Engineering

- *Configuration Management (CM).* CM is a system engineering process for establishing and maintaining consistency in asset performance, as well as functional and physical attributes. It considers the requirements in design and operational information for managing changes throughout the asset lifecycle. In summary, it assists with the management, planning, control, establishment, and ongoing maintenance of the objects of value (assets). The configuration management standards included in the IAF are:
  - *IEEE 828-2012 Standard for Configuration Management in Systems and Software Engineering Change Control.* The asset lifecycle processes that *IEEE 828* supports are requirements management, design, implementation, integration, verification, release / transition, operations, and maintenance, and project management
  - *ANSI/EIA-649 National Consensus Standard for Configuration Management.* This standard provides a definition for configuration management and a rationale for CM processes. It defines five primary CM functions: CM planning, configuration, and identification, change management, status accounting, and verification/audit. These are implemented via policies and procedures that define a standard change management process

The Systems Engineering subdomain connects with asset management, performance management, program management, supply chain management, organizational change management, enterprise architecture, requirements management, and digital engineering. The V-Model connects with ISO 55000 Project Delivery and Supply Chain Management, as it applies systems engineering for the project delivery process in not only the design and construction of built infrastructure, but also verification and validation to help provide assurance that the integrated system satisfies the 'voice of the customer'. According to the IAM Anatomy, the IAM Conceptual Model aligns also with the V-Model concept regarding Configuration Control and Management.

Digital Engineering

Digitalization of engineering and asset management is a global phenomenon driving major change in the way public infrastructure is procured, delivered, operated, and maintained. Digital Engineering relies on collaboration, largely using existing information and communication technologies which unlock more efficient ways of working through the asset lifecycle.

Digital Engineering is a collaborative way of working, leveraging digital processes to enable more productive methods of planning, designing, constructing, operating, and maintaining assets. It is achieved by creating a common data environment (CDE) that combines and aligns digital information systems and related data, including asset data, risk management, program/project management schedules and costs, requirements management, GIS, 3D BIM, and electronic document management. The CDE centralizes content from all players in the civil infrastructure supply chain to serve the asset owner.

The IAF follows standards and best practice from:

- ISO 19650 Organization and Digitization of Information about Buildings and Civil Engineering Works including Building Information Modelling (BIM)
- PAS[40] 1192 BIM Level 2 Requirements Framework. A framework for collaborative working and information requirements management
- According to the BS EN ISO 19650 suite and its predecessor ISO 1192, BIM is "the process of delivering relevant data about built environment assets through their lifecycle, in a structured, secure, and consistent manner to realize value to the economy, to the environment, and to society." BIM will enable the use of a shared digital representation of a built asset to facilitate design, construction, and operation processes, and form a reliable basis for asset management decision-making. The IAF follows the UK BIM Alliance recommendation to utilize BS EN ISO 19650 to create a digital twin. The goal is to provide clarity and satisfaction to asset owners through a true digital twin as a fully dynamic and real-time representation of their assets (as opposed to a static dataset)
- Transport for New South Wales is the leading transport and roads agency of the New South Wales Government, Australia. The IAF follows best practice from their TfNSW Digital Engineering (DE) Framework[41] and collaborative way of working using digital processes, to enable productive methods of planning, designing, constructing, operating, and maintaining assets. These DE processes provide an approach for digital information to become the key enabler of decision-making

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[40] Publicly Available Specification

41 The Digital Engineering Framework | Transport for NSW

With regards to digital engineering management, INCOSE, and the SEBoK supports the US Department of Defense (DoD)'s digital engineering strategy[42] to streamline the asset acquisition process, with the creation of models to represent all aspects of the asset system lifecycle, via model-based systems engineering (MBSE) as a subset of digital engineering in supporting requirements capture, architecture, design, verification, and validation. This way, digital engineering serves as the representation of system data in a format shareable between all the civil infrastructure supply chain stakeholders

This centralization of data is often delivered through a digital twin. A digital twin is a digital replica of a physical entity (asset), or the enterprise and its processes, people, places, systems, and devices. The digital twin can also represent an individual business function, business capability, or business process. The IAF employs enterprise architecture modeling notations (ArchiMate for the overall enterprise architecture, BPMN[43] for processes, UML[44] for data, etc.) and systems modeling notations (covered under the next subdomain) to capture the digital twin of the enterprise

- The *National Digital Twin Programme* (NTDp)[45], run by the *Centre for Digital Built Britain* (CDBB[46], a partnership between University of Cambridge and the UK Department for Business, Energy, and Industrial Strategy), was launched by HM[47] Treasury in July 2018, to deliver key recommendations of the National Infrastructure Commission's 2017 'Data for the Public Good Report'[48]. The NDTp's objectives are:
  - Enable a national digital twin as an ecosystem of connected digital twins to foster better outcomes from our built environment
  - Deliver an information management framework to ensure secure resilient data sharing and effective information management
  - Align a digital framework task group to provide coordination and alignment among key players

Digital Engineering also connects with the subdomain Asset Management and ISO 55000, and its Asset information Framework model (which establishes metadata requirements for O&M[49]).

The Digital Engineering subdomain interrelates with asset management (Lifecyle delivery, decision-making, and asset information), risk management, program management, supply chain management, enterprise architecture, requirements management, data, and information (common data environment or CDE, GIS) and systems engineering.

Systems Modeling

Model Based Systems Engineering (MBSE) is the use of models to capture future state designs that articulate the requirements of users and stakeholders and the interdisciplinary use of these

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42 Digital Engineering Strategy and Implementation (nist.gov)

43 Business Process Model And Notation

44 Unified Modeling Language

45 National Digital Twin Programme | Centre for Digital Built Britain (cam.ac.uk)

46 Centre for Digital Built Britain https://www.cdbb.cam.ac.uk/

47 Her Majesty's Treasury https://www.gov.uk/government/organisations/hm-treasury

48 Data for the public good (nic.org.uk)

49 Operations and Maintenance

models to conceptualize and construct systems in the enterprise from conceptual design through development and lifecycle (INCOSE 2007). The model constitutes a primary artifact of the systems engineering process.

The Systems Modeling subdomain includes these standards and guidelines:

- *OMG (Object Management Group) Systems Modeling Language™ (OMG SysML®).* SysML is a language for specifying, analyzing, designing, and verifying complex systems via graphical representation. SysML leverages the OMG XML Metadata Interchange (XMI®) to exchange modeling data between tools and is compatible with the evolving *ISO 10303-233* systems engineering data interchange standard
- *Lifecycle Modeling Language (LML)*. The LML ontology provides design elements that connect overlapping information needs across systems engineers (concerned with cost, schedule, performance), enterprise architects (capture and record layers of the enterprise architecture), process managers (document business processes), and program managers (cost, schedule, tasks, resources, risks)
- *Hetero-functional Graph Theory (HFGT).* HFGT translates a SysML graphical model into a mathematical model
- *Unified Modeling Language™ (UML)*. UML helps visualize, specify, and construct artifacts, standardizing the production of systems blueprints, conceptual business processes, system functions, and database schemas
- *The Reference Architectural Model (RAMI 4.0)*[50]*.* Similar to the *Smart Grid Reference Architecture (SGAM) Model*, *RAMI 4.0* can be leveraged to process complexity. RAMI 4.0 model connects the different participants in the civil infrastructure supply chain: business, IT or information, communications, system integrators, asset management practitioners, and the different enterprise departments. *RAMI* is a three-dimensional map showing how to approach the challenge of Industrie 4.0[51] in a structured manner. It is a service-oriented architecture that integrates different user perspectives and provides a common understanding of Industrie 4.0 technologies. It combines all elements and IT components in a layered asset lifecycle model.

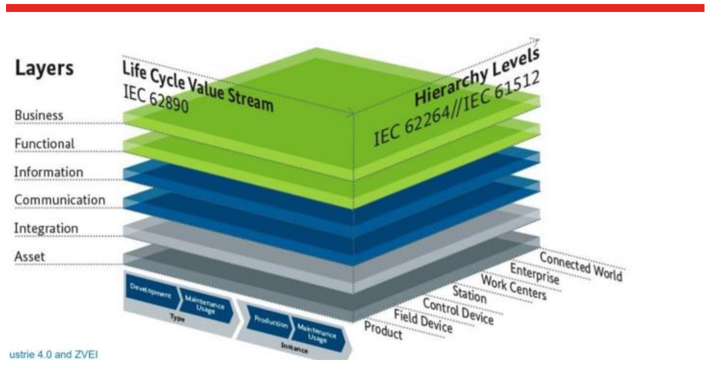

Figure 3-11: RAMI 4.0, Reference Architecture Model

The IAF leverages progress in making digital twin technology an integral part of MBSE, along with system simulation and the Internet of Things (IoT). The digital twin and the physical twin

[50] RAMI 4.0, Reference Architecture Model Industrie 4.0 (Industry 4.0) developed by the German Electrical and Electronic Manufacturers' Association (ZVEI) to support Industry 4.0 initiatives and Platform Industry 4.0

[51] The road from Industrie 4.0 to Infrastructure 4.0 – digital innovations make their way from our factories into our cities https://www.linkedin.com/pulse/road-from-industrie-40-infrastructure-digital-make-way-roland-busch/

can both be supported by a shared MBSE repository of the physical twin or asset data (design, configuration, performance, service history, maintenance) to a point where the MBSE models constitute the authoritative sources of truth. Digital twin technology can be expected to become a central application of MBSE because it can enable MBSE to span the full asset system lifecycle.

Civil infrastructure practitioners must manage data, information, and knowledge associated with both the technical, and with non-technical aspects of infrastructure management (e.g., workforce management and learning; organizational growth). The design of the IAF aligns with the subdomain "Collaborative Information Sharing, Integration, and Knowledge Convergence" to recognize the role of actors in modeling infrastructures as socio-technical systems[52].

The systems modeling subdomain of the IAF supports asset management, program management, enterprise architecture (process, systems, requirements, behaviors, motivations) internet of things, data, and configuration.

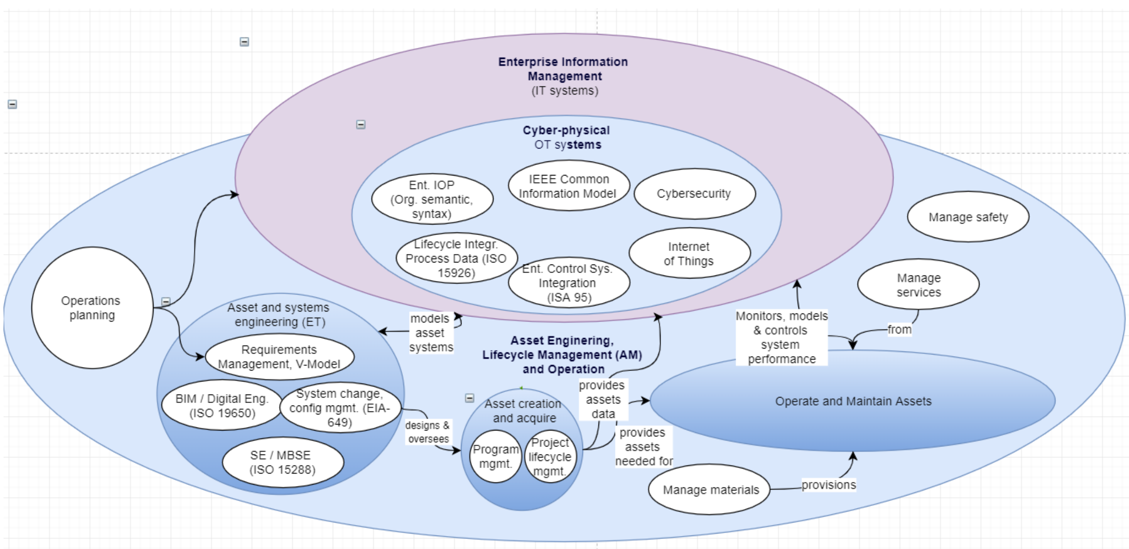

Figure 3-12: Asset and Systems Lifecycle Management

This subdomain of the IAF aligns with enterprise strategic planning and management controls (quality, performance, risk) asset management lifecycle, organizational change management, supply chain management, enterprise architecture (business architecture capabilities and business processes), and information and knowledge management (IoT, collaborative information sharing, data).

Enterprise Control Systems Integration

The IAF recognizes the *ANSI International Society of Automation 95 Enterprise-Control System Integration (ANSI/ISA-95)* as an interfacing standard. As the IAF is at the enterprise systems and not control systems level, the mapping provided by ANSI/*ISA-95* is not part of the IAF.

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52 Modeling infrastructures as socio-technical systems.

ANSI/ISA-95 defines the interfaces between control functions and other enterprise functions based upon the *Purdue Reference Model* for the IEEE Common Information Model (CIM), as published by ISA. Its goal is to reduce the risk, cost, and error in implementing these interfaces and to provide consistent terminology for communications across suppliers and participants. It describes in detail an abstract model of the enterprise, including manufacturing control functions and business functions, and their information exchange, leveraging common terminology and including data models and exchange definitions.

The *ANSI/ISA-95* automation pyramid presents the following levels: Level 4 (Enterprise Resource Planning or ERP, Level 3 (Manufacturing Execution Systems or MES), Level 2 (Monitoring, Supervision, Control), Level 1 (Sensing and Actuation, IoT) and Level 0 (the actual production process).

3.3 Aligning the Four Domains

The first step in developing the IAF was to produce an ontology describing the four main Domains and their underlying Subdomains, Standards and Guidelines in a hierarchical format. The process consisted of an initial identification of standards, guidelines, bodies of knowledge and best practices related to the four domains and relevant to the requirements of the framework, followed by the study and determination of their key elements and connections with one another. This produced an inventory the principles, practices and relationships commonly used for managing civil infrastructure system.

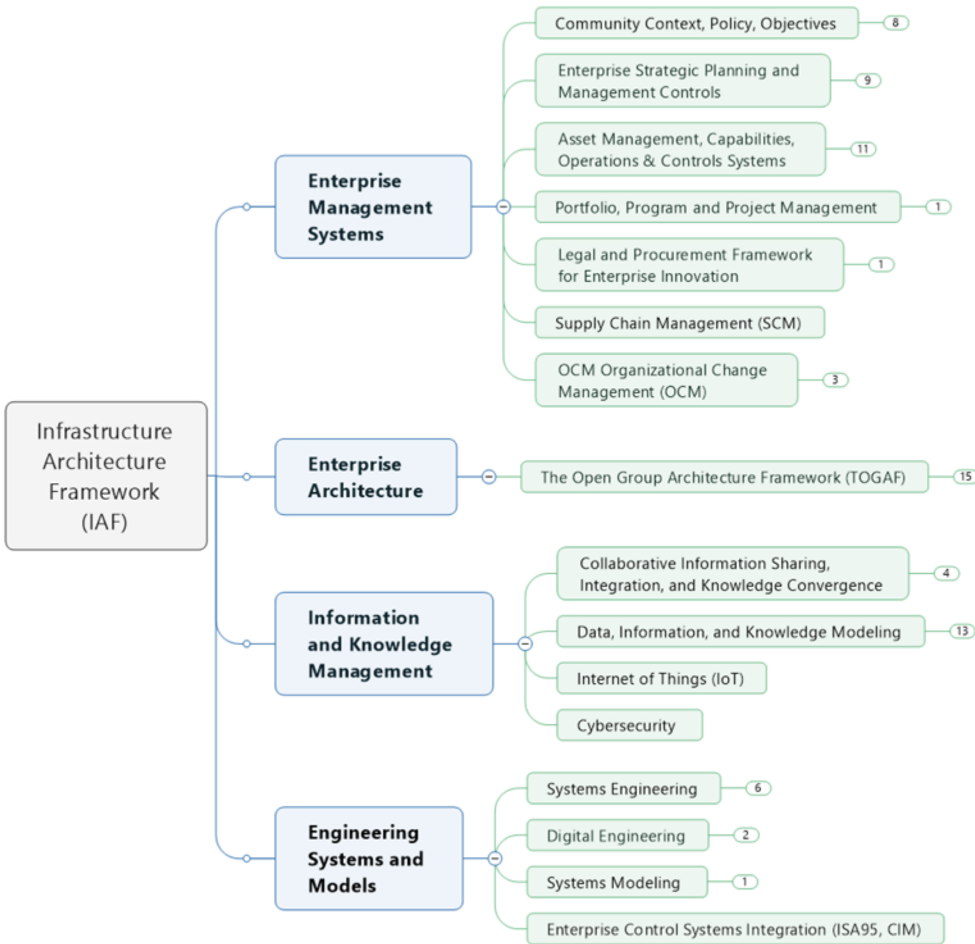

Figure 3-13: Infrastructure Architecture Framework Ontology

The value of the framework resides specially in those connections established between components. The interconnections between domains and subdomains (and their standards or guidelines) were identified through connecting elements. The IAF experts and community reviewed and critiqued the framework's structure and components, and then provided essential design and input to adequately connect the different IAF levels. The project applied systems thinking to move from the initial ontology of individual disciplines to an enterprise system model, which unveiled and enriched the interconnections between system hierarchy levels, disciplines, and standards.

A Systemigram of the IAF was constructed using the SERC SystemiTool[53] to visualize the domain and subdomain elements and depict the flow of information, resources, and actions. A Systemigram is a formal visualization and modeling approach, capturing a system's context and its architecture, to guide the transition from narrative to computational modeling and represent complex relationships for further analysis. First developed by John Boardman, it provides a powerful systems analysis tool for business architecture, capturing the socio-technical systems

[53] Systems Engineering Research Center https://sercuarc.org/serc-tools/

elements, logical flows, and the larger context.[54,55] It does not remove the complexity from systems, but it can make complex systems understandable. It models the narrative as a set of nodes and links that tell a story, enabling understanding of system of systems dynamics and stakeholder views. The narrative is decomposed into individual but related threads showing the flow of information, resources, and actions.

The Systemigram of the IAF provided a common foundation for group discussions. Technical experts and other stakeholders were engaged in interviews, workshops,

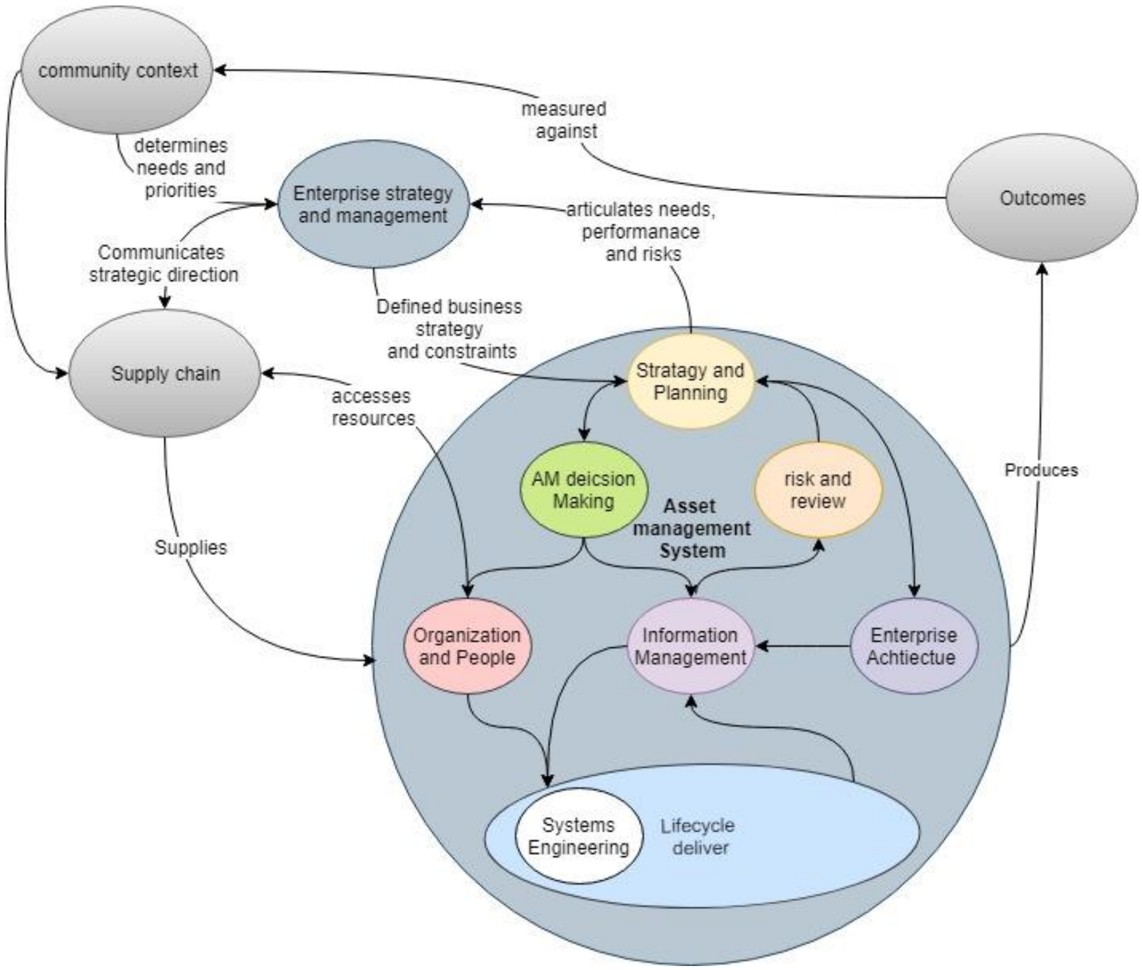

Figure 3-14 Simplified Systemigram of IAF

case studies and roundtables to gain deeper insights for depicting the overall system. Leveraging these insights, we converted information about the individual domains into

[54] Boardman, J. & Sauser, Brian. (2013). Systemic Thinking: Building Maps for Worlds of Systems.

[55] Soft systems methodology (SSM) is an approach to organizational process modelling and it can be used both for general problem solving and in the management of change

knowledge about the system context and dynamics by tracing the interconnections of domain elements[56].

The complete Systemigram of the IAF is illustrated in Appendix F. It provides a holistic, enterprise view of infrastructure as a socio-technical system at the strategic, management and operations levels: the context in which infrastructure operates, its boundaries, the domains, and subdomains and their interconnections. Gathering information on the four domains and pouring over the relevant standards and practices to produce the IAF framework was useful for understanding the constituent parts, but insufficient for creating a concise system description of the whole enterprise. The Systemigram does this in a way that is digestible, analyzable, and linguistically recognizable among diverse stakeholders in the infrastructure community.[57]

[56] The Future Exchange of Digital Engineering Data and Models an Enterprise Systems Analysis https://cser.info/wp-content/uploads/2019/05/15.1_The-Future-Exchange-of-Digital-Engineering-Data-ans-Models-an-Enterprise-Systems-Analysis_McDermott.pdf

[57] Boardman, J. & Sauser, Brian. (2013). Systemic Thinking: Building Maps for Worlds of Systems.

4 Applications

Can we apply a common architecture framework to civil infrastructure?

Our fundamental question is not one of developing the Infrastructure Architecture Framework, it is about applying it. Having developed a draft version of the IAF, we brought together an expert panel to tackle two questions:

- Does the proposed Infrastructure Architecture Framework offer new insights across disciplines for understanding real world use cases from our existing New York civil infrastructure?
- Do real world use cases point to opportunities to extend the Infrastructure Architecture Framework across disciplines to improve the management of civil infrastructure?

4.1 Use Cases

These questions were explored in "deep dive" facilitated workshop sessions with our distinguished panel of experts through uses cases from the water, energy, and transport sectors. The experts mapped the use cases onto the draft IAF from the strategic level at the top of the IAF Systemigram, through the management level at the center and the lifecycle of the physical Assets and Operations found at the bottom and finally through to the outputs, outcomes, and benefits. Using the four IAF domains (Enterprise Management Systems, Enterprise Architecture, Information and Knowledge Management and Engineering Systems and Models) as viewpoints, the panels were able to develop holistic, multidimensional solutions to these questions. The use cases and their solutions are summarized below.

4.1.1 Water - Digital Twin Use Case

Water Utility (WatU) is responsible for the management of the urban water cycle with a vision for holistic management in a smart city context. WatU wants to build a digital twin to integrate information across systems with the goal is to promote a culture of Smart Water Management for the efficient usage of resources among all stakeholders. The envisioned digital twins would be used to forecast flooding and water quality issues, improve city services and responsiveness, and ensure resilience of water infrastructure.

Holistic management of the city water cycle requires detailed resolution from many models and domains including regional environmental management, customer service, asset management, operational systems, GIS, and SCADA[58]. Using the IAF, this panel developed the conceptual design for the Digital Twin, integrating Process-Organization-Technology-Information at the community, strategic, management and operations levels.

[58] Supervisory Control and Data Acquisition

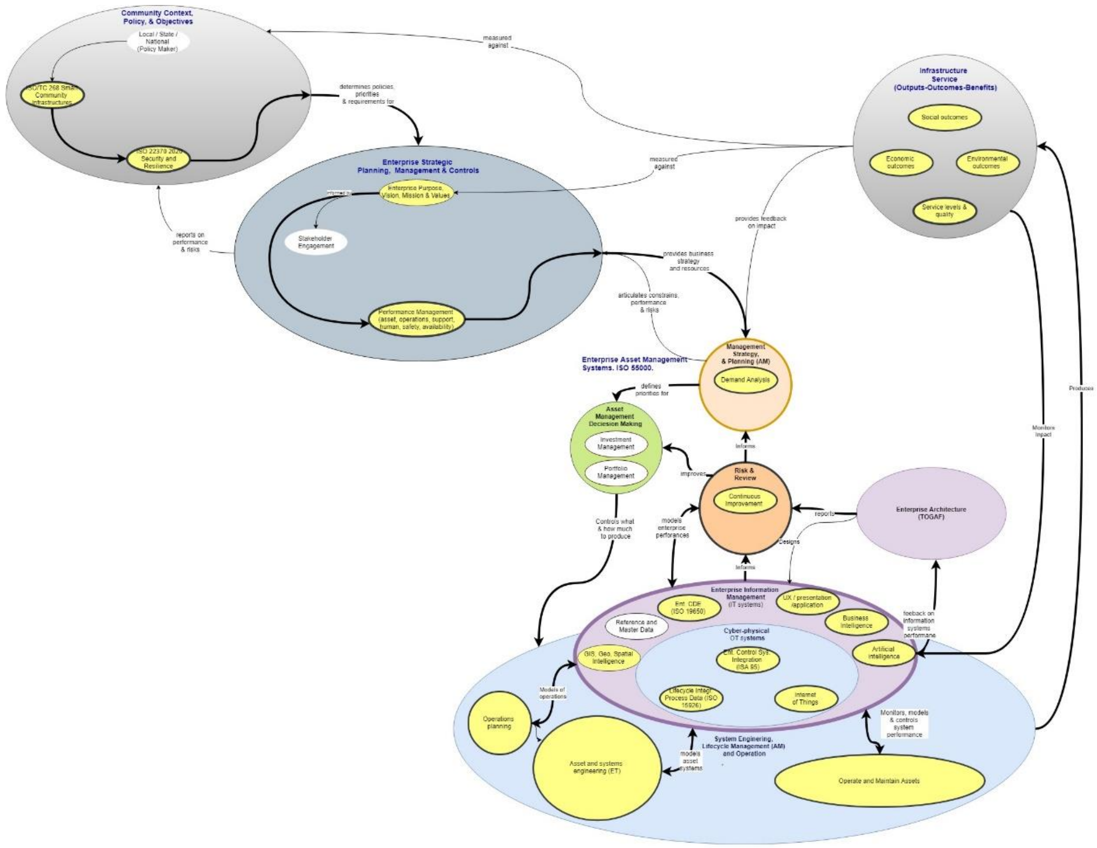

Figure 4-1 IAF Systemigram – Water Utility Digital Twin Use Case

Beginning at the community level, the standards for smart infrastructure, security and resilience define the regional context, priorities and high-level outcomes required from the Water Unity as a system within a wider system of systems. Stakeholder engagement informs WatU's enterprise purpose, leadership, performance management and risk framework.

The enterprise asset management system translates the business strategy into a decision framework for lifecycle management of the water system to produce the optimal social, economic, and environmental outcomes from the available resources. The enterprise architecture of the proposed digital twin would align business capabilities, information models and technology infrastructure with the business strategy with a digital representation of the underlying natural environment and manmade physical systems for holistic management.

The enterprise information management, cyber-physical systems, and model-based system engineering follow standards for lifecycle integration of data, models, sensors, and controls. This includes the required integration of the engineering, operations and information technology needed to model the asset systems and operations within the regional geospatial context to promote smarter management, improve water quality and provide greater system resilience.

4.1.2 Power - Asset Monitoring Use Case

The Power Company (PCo) is a large utility, with a dozen generating facilities (50% from renewable) and a more than 1,500 circuit-miles of transmission lines. PCo's vision includes being a digital utility to enhance productivity, reliability, safety, customer's experience, compliance, and revenue management outcomes. PCo envisions leveraging connectivity, big data, IoT and business analytics to drive actionable business insight to better serve their customers, employees, and other key stakeholders. The goal is to increase performance, assure compliance and lower risk through real-time monitoring and predictive analysis of asset health of power generation and transmission assets.

The conceptual design calls for a Smart Operations Center integrating Process- Organization-Technology-Information to analyze the health and performance of assets in near real-time to reduce potential service outages and reduce repair and replacement costs while minimizing operational risks. The proposed solution leverages connectivity, big data, IoT, and business analytics to drive actionable business insight to serve customers, employees, and other stakeholders. The full integration of traditional Business Applications with Operational Applications such as Energy Management System, Supervisory Control and Data Acquisition (SCADA), Outage Management System, Asset Performance Management, etc., is to be determined. The Enterprise Architecture will extend PCo's data centers and control centers with cloud and Internet of Things (IoT) capacities.

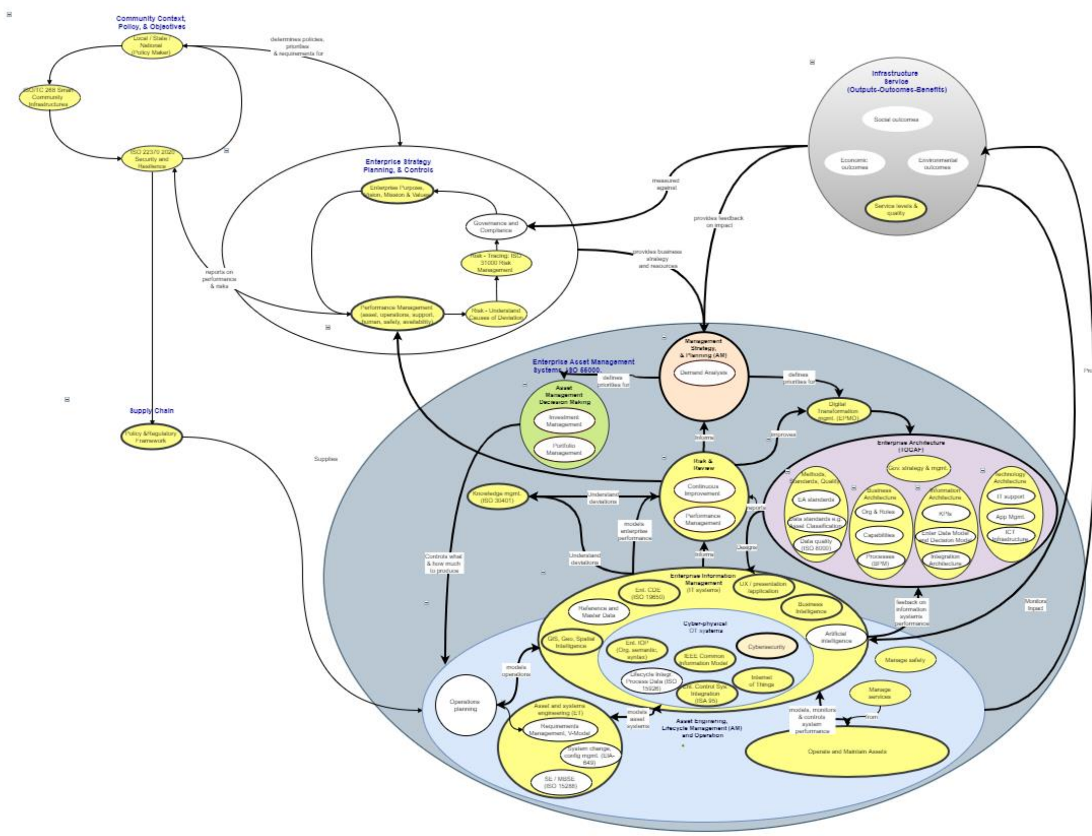

Figure 4-2 IAF Systemigram – Power Utility Asset Monitoring

The vision for a digital utility comes from executive leadership as a way to advance the enterprise purpose and the community policy objectives for smart community infrastructure and greater resilience. The enterprise business strategy prioritizes investments for the design and construction of a Smart Operations Center including the required modifications to existing

Scada systems, other operational applications, and the deployment of IoT sensors embedded in equipment and deployed in the field.

A Digital Transformation Office (DTO) was created to drive the implementation of the enterprise digital transformation with a multi-year program. Working at the solution level, the PCo is developing an Enterprise Architecture (EA) per the digital transformation roadmap. The Enterprise Architecture, once completed, will provide IT and OT[59] managers with signature-ready recommendations for adjusting policies and projects to achieve target operating model. Enterprise information management from the common data environment and integration with operating systems enables easy visualization of real time operations, system performance and business intelligence in geo-spatial context.

The updated Operations Center will make it possible to analyze the health and performance of PCo's power generation and transmission assets in near real-time. The Center's asset health monitoring and diagnostic tools reduce potential service outages, reduce repair and replacement costs while minimizing operational risks.

4.1.3 Transit - Performance Management Use Case

Public Transit Company (TransCo) operates a network of trains, transit, light rail, and buses. The Centennial Vision and Plan commits to modernizing the capital plan and information systems aligned with stakeholder objectives for sustainable, smart, and inclusive development. The Plan calls for a new performance management framework that supports sustainability objectives and better information management that provides the basis for continuous improvement. TransCo's approach to sustainability is based on the triple bottom line, evaluating TransCo's performance with respect to its impacts on the natural environment, healthy communities, and workforce and economic vitality

The solution proposed by the panel included a full range of activities to obtain the full value from data assets, such as policies, standards and governance, integration, information architecture, technology, analytics, and organizational change management. Data was characterized as the new "life blood" of a reimagined TransCo. As data flows between systems, databases, processes, and departments, it carries with it the ability to make the organization smarter and more effective. A Digital Transformation Office (DTO) was created to drive the modernization and integration of the information systems to improve TransCo operations, efficiency, effectiveness, and outcomes. As part of an enterprise digital transformation, the DTO was tasked with establishing a common information model as the single source of truth for performance information.

[59] IT/OT convergence is the integration of information technology (IT) systems with operational technology (OT) systems

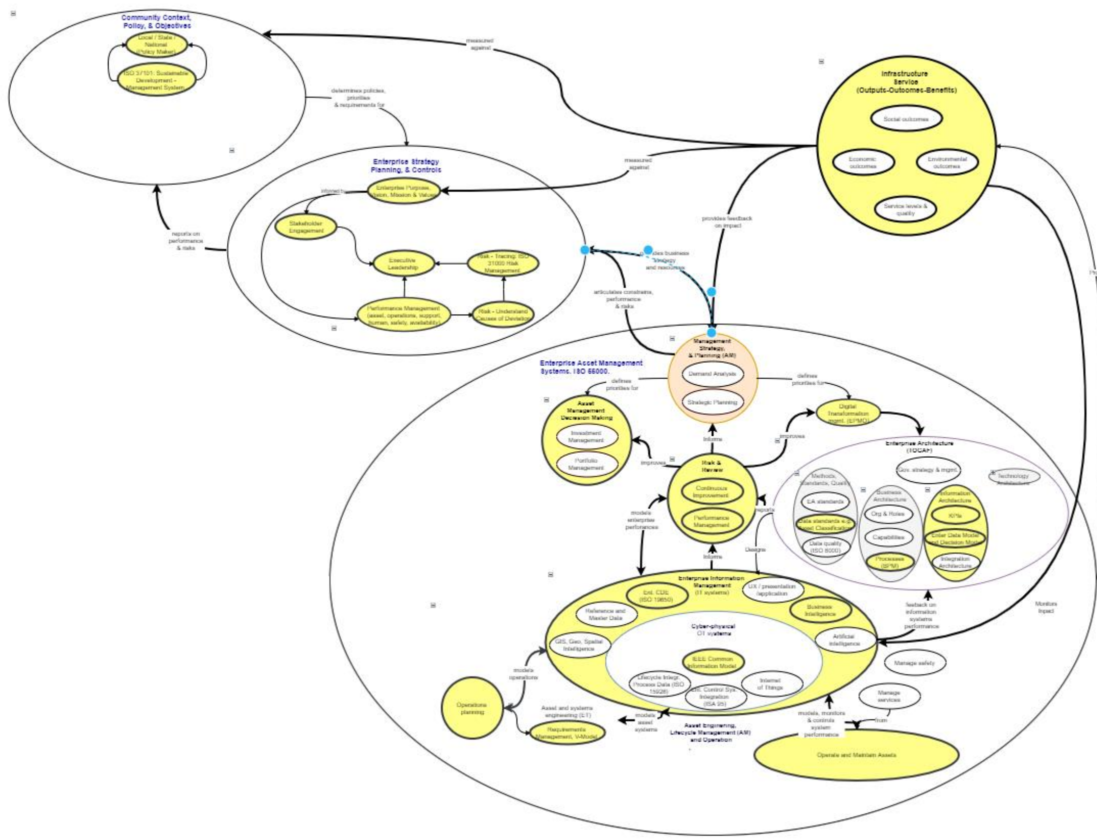

Figure 4-3 IAF Systemigram – Transit Performance Management

Management of sustainable development in communities can be established as a framework for fostering smartness, sustainability, and resilience. This requires assessing progress towards sustainable development by defining what needs to be monitored and measured related to the TransCo's impact on the communities' economic and social progress and protection of the natural environment, pushing performance measurement into the realm of sustainability.

Key performance indicators are assigned to social, economic, and environmental goals to monitor the organization's progress towards achieving sustainable development goals and objectives. The enterprise performance management system can be retooled to support the planning and execution of the sustainability strategy, providing the ability to monitor performance measures, provide analysis and manage reporting.

The asset management strategy and plan reflect the business strategies for sustainability and priorities for decision making. The risk and review function of the asset management system includes monitoring both the asset performance and health and the social, economic, and environmental impact of the organization's assets and services. Enterprise information management data standards, models and schema make sure the right data of the right quality is accessible to processes and people that need it using a common information model as a single source of truth.

As a result, TransCo is able to report sustainable performance measures consistently internally and externally. Stakeholders can see the value of this reporting and come to expect regular measurement and more explicit linkages between the measures and the organization's decisions. TransCo's staff and stakeholders are then able to engage in much richer conversations about the trade-offs among policy and investment decisions and the best opportunities for their region or state to reach its sustainability goals.

4.2 Realizing Benefits

The use cases demonstrated that the architectural framework is broad and flexible enough to accommodate a variety of asset-intensive infrastructure organizations and businesses. Each of the IAF domains worked well on their own but they added value to an integrated approach, capturing the most important aspects of the standards applied to the use cases. The IAF supported the integration of people, process, technology, information, and physical assets aligned to organizational strategy and outcomes. It helped users visualize system properties like sustainability and resilience, the balancing of cost, service delivery and organizational constraints over time. The IAF appears to be an excellent model to help understand the role of infrastructure as part of larger processes and systems within a community context. The use cases also led to important observations on how enterprise change management could help address problems of organizational delivery.

> *"The IAF proved to be comprehensive, well thought through and articulated"*

5 Opportunities

5.1 From Theory to Application

The purpose of the IAF is to address the need to align different standards for managing physical civil infrastructure in a holistic, integrative manner with an overall systems view. The vision for IAF is its utilization as a tangible reference architecture by civil infrastructure operators so they can interface across different markets and sectors as well as approach their own evolution holistically. Along the way, the IAF will need to be modified and expanded in order to adapt to the evolving complexity of infrastructure systems.

This project demonstrated that an enterprise architectural framework can provide a systemic approach for describing complex sociotechnical infrastructure systems, their purpose, services, standard, integration and content. Taking the IAF forward requires engaging a community of enterprise system engineers and architecture practitioners focused on transformation of infrastructure systems to support smart, sustainable, and resilient communities. While this report describes the initial steps in the journey to create a useful, viable, and dynamic framework, this section discusses possibilities lying beyond the work to date.

5.2 Areas for Future Development

While the application of the current version of the IAF by asset owners and academia is top of mind, there are also many opportunities for research to address its deficiencies through enhancement and extension. Here are a few of the suggestions made by our panel of experts.

Sustainability

While the intent of the IAF is to help build sustainable and resilient infrastructure systems, the current version of the IAF does not include or reference sustainability standards or frameworks. Future versions may expand the scope of the IAF to explicitly include sustainability, however it is anticipated that this will be challenging. According to the OECD[60] "There is a plethora of internationally, nationally and locally endorsed definitions, approaches, standards, principles, guidelines and frameworks in place for sustainable infrastructural development." [61]

A more tractable approach may be limiting the expansion to include only emerging Smart Sustainable cities standards[62] and emerging standards for measuring the carbon footprint of buildings (ISO 16745) and the carbon footprint of products (ISO 14067).

Incident Management

Natural disasters and other abnormal situations are the critical point where infrastructure organizations need to integrate the management of internal operations, processes and systems with external organizations and systems. The US National Incident Management System

[60] OECD: Organisation for Economic Co-operation and Development

61 OECD Overview of selected sustainable infrastructure standards and norms https://www.oecd-ilibrary.org/sites/57e511f1-en/index.html?itemId=/content/component/57e511f1-en

62 apo Huovila, Peter Bosch, Miimu Airaksinen, Comparative analysis of standardized indicators for Smart sustainable cities: What indicators and standards to use and when? https://www.sciencedirect.com/science/article/pii/S0264275118309120

(NIMS) is designed to do just that. NIMS provides stakeholders across the whole community with the shared vocabulary, systems and processes to successfully deliver the capabilities described in the National Preparedness System. NIMS and other incident management systems could be incorporated into the IAF.

Geographic Information Systems (GIS)

GIS has demonstrated an ability to integrate different infrastructure views. The Open Geospatial Consortium (OGC) and ISO standards are widely implemented at national, regional, and local levels. Most geospatial technology vendors, as well as open-source solutions, support these standards. Integration across and between GIS systems supporting different infrastructure providers would greatly improve the progress towards a synthesis that is already occurring.

Human Dimension

Although our target enterprises (e.g., MTA, NYPA) face more challenges with regards to managing people than with technical aspects (technology, IT, management), the issue most frequently cited by our community of experts is the lack of a "human dimension" to the framework. Various terms were used in describing this gap: human-centric design, socio-technical systems, human-technology systems, "data for the public good", etc. Integration of a human dimension into the IAF using a systems engineering-based approach is an open challenge and we encourage active research into this expansion.

To make the IAF more human-centric, the following enhancements could be considered among others:

- The subdomain Organizational Change Management (people, change, etc.) can be considered alongside the subdomain Collaborative Information Sharing under Information and Knowledge Management.
- Collaborative Information Sharing includes guidelines about Knowledge Management, Collaborative Business Relationship, Maturity and Competency, Training and Education. The IAF can provide additional standards and guidelines under this subdomain to improve it value in managing complex transformational projects.
- The Organizational layer of Enterprise Architecture within the IAF is based on people and their roles. This layer can be modeled along with the other layers of the EA (process, systems, data…) that constitute the civil infrastructures we target with our IAF.
- The IAF could capture best practices on Workflow Provenance, recommendations for how humans capture and use data and systems for predictability in digital workflows.

Management of Change

Change is a topic which is currently not addressed comprehensively within the IAF, although several change-related standards and guidelines are included. MSP (included under Enterprise Management Systems/Project, Program and Portfolio Management) considers change from four aspects - people, organization, technology, and information and is focused on governance and stakeholder management. TOGAF (included under Enterprise Architecture) is focused on change (transformation) through application of enterprise architecture.

There are many existing models for describing comprehensive change at the IAF System of Interest (organizational) level which can be considered for future versions of the Framework. Perhaps more urgently, a guide for applying the IAF within the organization, directed toward the changes required to ensure its success and including the IAF in the target operating model, needs to be developed.

Risk Management

The existing Risk Management component of the IAF, included under Enterprise Planning and Management, only acknowledges deviation and how to track it. It does not provide adequate tools to dig into causes. This could be address by extension of the IAF to include additional standards within the ISO 9000 series of quality management standards and the identification and addition of relevant guidelines.

Legal and Procurement Framework

A logical and practical extension of the IAF is the inclusion of standard forms of contract, contract templates and contract guidance for managing major projects. These are well-defined and readily available for reference from the International Federation of Consulting Engineers (FIDIC) and others.

A more substantive and valuable, but likely more challenging, approach is to integrate the learnings from the UK's Project13 into the IAF. [Project13 is an industry-led response that seeks to develop a new infrastructure delivery business model – based on an enterprise, not on traditional transactional arrangements – to boost certainty and productivity in delivery, improve whole life outcomes in operation and support a more sustainable, innovative, highly skilled industry.]

Maturity Models

A maturity model is a necessary tool that helps assess the current effectiveness of an organization and what capabilities are needed to improvement improve performance. *TOGAF Architecture Maturity Models* provides techniques for evaluating and quantifying an organization's maturity in enterprise architecture.[63] *Capabilities Maturity Models (CMM).* CMM in general and the Standard CMMI Appraisal Method for Process Improvement (SCAMPI) in particular are compatible with and similar to *ISO 9001*, with the addition of establishing a framework for continuous process improvement.[64] Developing a maturing model aligned with industry standards is on the short list of improvements of the IAF.

5.3 Pathways for Systemic Change

Earlier in this section, we set out some recommended actions that can be taken to both apply and adopt the existing version of the IAF and continue to enhance it. Stakeholders in the framework expressed a clear desire to grow a community of practice; develop the enterprise system approach to infrastructure management; link-up with local, national and international efforts applying similar methodologies; and demonstration practical application in the real work.

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63 Architecture Maturity Models (opengroup.org)

64 Standard CMMI Appraisal Method for Process Improvement (SCAMPI) A, Version 1.3: Method Definition Document (dtic.mil)

The roadmap proposed below provides a view of how these activities could be carried out over the next three plus years with continued engagement of the stakeholders and adequate support, research, and development, and building capacity for system level impacts.

5.3.1 Establishing an Infrastructure Leadership Group

The systemic nature of challenges such as the energy transition, digital transformation, and sustainable development means that they cannot be solved by infrastructure operators, government actors, or academic institutions acting alone. Transforming infrastructure at enterprise scale requires a holistic vision among multiple constituents concerned with the viability of infrastructure systems within the socio-economic context. Leaders from many organizations must work together across institutional boundaries towards common goals, integrate capabilities and collaborate on outcome-oriented actions for large-scale system change.

Transformational journeys cannot be prescribed in advance due to the complexity and emergent nature of system change. Instead, pathways of possibilities arise from the engagement of local stakeholders with overlaying interest and a shared sense of the potential impacts of mutual concern. An infrastructure leadership group would open pathways for transitioning to more sustainable forms, introducing the new approach, problem solving the challenges, encouraging system level breakthroughs, and moving the dial on community scale outcomes. Guided by a shared understanding of the significance of their role in systems larger than their own organization, participants will gain profoundly in their ability to perceive, envision, and implement changes in infrastructure from a system approach.

The UK **Infrastructure Client Group (ICG)** was established in 2010. It focused initially on improving the efficiency of infrastructure delivery, operation, and management with the goal of lowering costs by 30 per cent and reducing time by 50 per cent. Today the ICG continues to demonstrate the value of effective collaboration between government and industry in the development and exchange of best practices and delivery improvements for the benefit of the economy, society, and the environment.

A model for New York may be the Infrastructure Client Group (ICG) in the United Kingdom. The ICG brings together key infrastructure organizations with a system-based view of infrastructure to deliver a set of common objectives and improvements to the way the UK meets its infrastructure needs[65,66]. Similarly, bringing together the major infrastructure providers in the New York metropolitan region could build a community of practice looking at infrastructure as a socio-technical system of systems, supporting the holistic transformation of regional transportation, water, power, and communications infrastructure enabled by passage by the American Congress of a $1.2 trillion infrastructure package in November 2021.

5.3.2 Engaging the Research Community to Build Knowledge

The combination of enterprise architecture with systems engineering creates a valuable framework for integrating diverse academic programs in engineering, information technology,

[65] Infrastructure Client Group | Institution of Civil Engineers (ice.org.uk)
[66] ICG_1_October_2014_event_Pamphlet.pdf (publishing.service.gov.uk)

environmental science, urban planning, and other fields in support of system change resulting in more sustainable and resilient infrastructure. Guided by the application of the IAF and the vision and priorities defined by the infrastructure leadership group, academic research and training programs could align and integrate resources in response to identified gaps in knowledge and industrial capabilities. Evidence of this potential was visible during the early stages of this project when leading civil, systems and software engineering programs requested support to introduce the IAF into their current research and training programs.

Moving forward, a universal body of knowledge can be created from research chartered and published on the development of the IAF, its application, extensions such as those in Section 7 (e.g., risk management, sustainability), and challenges defined by the infrastructure leadership group. Professors can develop advanced training modules, capstone projects, and/or interdisciplinary programs at the undergraduate and graduate level. The transition to smarter, more sustainable, and resilient infrastructure presents grand challenges for masters and PhD students interested in applied research.

University-industry collaboration can stimulate innovation to solve complex problems, create a more skilled workforce, and drive economic growth. Industry gains work-ready talent with specialist knowledge and practical training, and universities benefit by having opportunities to work on relevant technologies and challenging problems. Opportunities have already been provided by the Systems Engineering Research Center (SERC, Stevens Institute of Technology) and the Department of Civil and Environmental Engineering at Carnegie Mellon University and we welcome additional inquiries.

5.3.3 Building a Community of Practice

The sustainability and resilience of urban infrastructure systems is contingent upon the transformation and adaption of both the physical infrastructure and the organizations that manage that infrastructure. One approach to accelerating organizational transformation is creating a community of practice (CoP), consisting of practitioners and experts collectively developing and extending the IAF and sharing state-of-the-art enterprise system engineering and architecture tools and knowledge.

Change rarely happens as a result of top-down, pre-conceived strategic plans, or from the mandate of an outside authority. Change more often begins as local actions spring up simultaneously in many different areas. If these changes remain disconnected, nothing happens beyond each locale. When local actions become connected, change can emerge as a powerful system with influence at a more global or comprehensive level. The value of collective learning in the CoP lies in the expertise of the community and its unified sense of mission and purpose. Change comes from a community of people who discover they share a common cause and vision of what is possible.

> *"A community of practice is a group of people who are informally bound to one another by exposure to a common class of problems."*
>
> Brook Manville, Director of Knowledge Management at McKinsey & Co.

An urban infrastructure systems CoP would include both academic and industry experts collectively addressing problems and sharing knowledge on the development and application of systems approaches to infrastructure sustainability, including challenges such as energy transition and digital transformation. Over time, individuals who interact and collaborate to address problems and share knowledge evolve trusted relationships and collective learning to allow the group to adjust to change.

5.3.4 Supporting Application of Innovation in Real World Projects

Accelerating system innovation in the infrastructure sector requires working in the real-world to intentionally reshape the way people, organizations, and technology work together. Diverse stakeholders, including infrastructure operators, suppliers, and research organizations, must work collaboratively to achieve shared goals, overcome obstacles and obtain benefits. Several key factors can help drive open innovation in the infrastructure sector. These include the adoption of new systems approaches to delivery, operations and management and making full use of new technologies to link BIM, IoT data and digital twins. Leadership and support from the Infrastructure Leadership Group will be necessary to define the challenges and determine priorities, and to cultivate support for the long-term vision. Equally important is growing a community of researchers and practitioners with the knowledge and ability to generate innovative ideas, implement innovative solutions and scale adoption.

The key to successful transformational change is to keep stakeholder needs at the forefront resulting in outcomes with tangible benefits. A community of practice within the asset-owning organizations, supported by the broader practice network, can best advocate and evolve the IAF vision and concepts. Ideally, the IAF would be tested in real cases provided by asset owners to ensure its relevancy, application to reality and currency. Running a broad range of “proof of concept” projects makes it possible for stakeholders to see the benefits that a system change initiative provides while giving the Infrastructure Leadership Group the opportunity to gather valuable feedback. It also brings people together for collaboration in real-life settings where innovation can be tested and integrated into large-scale systems. The application of innovative practices in the real-world proof of concepts allows early assessment of the socio-economic implications of new technological solutions by demonstrating the validity of new services and business models. Moving from theory to practice opens practical pathways for larger scale system change that come from measurable benefits and tangible outcomes.

5.4 Compelling Need to Act

Passage by the American Congress of a $1.2 trillion infrastructure package in November 2021 sets the stage for a massive overhaul of transportation, water, power, and communications infrastructure in the New York City metro area. Funding will go to building the extension of the Second Avenue subway line and the revitalization of the Port Authority bus terminal. Amtrak’s high-speed rail proposals for the Northeast corridor are slated to receive more than $6.5 billion for capital renewal backlog projects as well as $3.6 billion for intercity passenger rail grants. JFK International Airport could get $295 million and LaGuardia Airport $150 million for upgrades and repairs and New York State may see $90 billion for water infrastructure upgrades and $100 million for the state to expand and subsidize broadband coverage[67].

[67] https://gothamist.com/news/new-york-reap-billions-dollars-mass-transit-monumental-infrastructure-bill

This investment “has the potential to transform New York City and its surrounding region.”[68]. Transforming infrastructure systems – such as water, energy, or transportation – is monumental task requiring coordinated action by many actors, organizations, governments, and civic institution. Enterprise architecture and systems engineering have been used to design, integrate and manage complex systems as diverse as deep space exploration, global financial platforms, and national health care. There could be no better time to embrace a system-based approach to infrastructure delivery and management.

[68] https://www.nytimes.com/2021/11/15/nyregion/infrastructure-bill-new-york.html

Appendices

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Lead Organizations

United Engineering Foundation

The United Engineering Foundation advances the engineering arts and sciences for the welfare of humanity. This project was made possible through the support of a grant from the United Engineering Foundation and the active contributions of its Founding Societies.

The New York Academy of Sciences

The mission of the New York Academy of Sciences is to drive innovative solutions to society's challenges by advancing scientific research, education, and policy.

Mott MacDonald

Mott MacDonald is a global engineering, management, and development firm. Our purpose is to improve society by considering social outcomes in everything we do, relentlessly focusing on excellence and digital innovation, transforming our clients' businesses, our communities, and employee opportunities.

Project Team

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Now a Senior Advisor to the Academy, Dr. Costley was formerly Director of Physical Sciences, Sustainability and Engineering, overseeing the Academy's portfolio of sustainability and hard sciences initiatives. She worked closely with the Academy's partner organizations (corporations, foundations, government agencies and individual stakeholders) to develop conferences, symposia, workshops, and other sponsor-driven programs.

Prior to joining the Academy, Dr. Costley provided technology leadership to such leading firms as Credit Suisse, DoubleClick, and Bell Labs, and was also a principal of her own consultancy where she conducted research on major technology trends and advised corporations on technology strategy and governance.

Michael Salvato

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Mr. Salvato is Vice President of Infrastructure Advisory at Mott MacDonald, a global engineering, management, and development consultancy guiding our clients through many of the planet's most intricate challenges.

He has over 35 years of experience in infrastructure planning, engineering, construction, program management, economics, finance, asset management and information systems. Mr. Salvato retired from the NY Metropolitan Transportation Authority as the Program Executive and Director of Enterprise Information and Asset Management In 2018.

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Carlos Maestre has developed his career in sectors such as industrial manufacturing, financial services, transportation, and the AEC sector, helping enterprises achieve their digital and business transformations. He is deploying his skills in program management, enterprise architecture, information management, digital technologies, and asset management for the continuous coordination and development of this Infrastructure Architecture Framework.

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Michelle Bryner is AIChE's Director of Publications, Facilitation & Business Development, a role she assumed on January 1, 2021. In this capacity, she leads two of AIChE's business units — Publications, where she oversees six peer-reviewed journals and new books, and Facilitation & Business Development, in which she manages facilitation efforts, community development, and grants.

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Sarah Ewing is a Senior Engineering Specialist at AIChE, with 5 years of experience facilitating meetings and helping to achieve Institute goals. Sarah has facilitated workshops for AIChE communities such as the RAPID Manufacturing Institute, the Center for Hydrogen Safety, and the Institute for Learning & Innovation. She earned a Bachelor of Science in Chemical Engineering from University of California, Irvine.

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Thomas McDermott currently serves as Deputy Director and Chief Technology Officer of the Systems Engineering Research Center at Stevens Institute of Technology in Hoboken, NJ, as well as a consultant specializing in strategic planning for uncertain environments. He serves as Director of Strategic Integration on the Board of the International Council on Systems Engineering.

Mark Bew is the CEO for The Cohesive Companies, a wholly owned business unit of Bentley Systems. Bew joined Bentley Systems with its 2020 acquisition of consultancy PCSG, a digital advisory services and solutions in the transportation sector. Prior to PCSG, Bew held roles with Costain and URS-Scott Wilson. Based in London, Bew also chaired the UK government's BIM Task Group, which led the work to embed digital techniques and processes within major UK public sector infrastructure programs.

Nora El-Gohary is an Associate Professor in the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign. She is an expert in data analytics and artificial intelligence (AI) for the development and operation of sustainable buildings and infrastructure systems, including information modeling, information extraction, data fusion, machine learning, and big data analytics. She currently serves as the Chair of the Executive Committee of the American Society of Civil Engineers (ASCE)'s Computing Division, the Chair of the Executive Committee of the ASCE's Construction Research Council, and the Co-Chair of the Transportation Research Board's Information Systems in Construction Management Subcommittee. She also currently serves as Associate Editor for the ASCE Journal of Computing in Civil Engineering.

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John Palmer currently serves as New York Power Authority's (NYPA) Principal Enterprise Architect. He introduced the practice of business architecture at NYPA and is using that approach to develop NYPA's energy management and renewable business products. In a previous job at IBM, he was responsible for integrating IBM's supply chain, insurance, and financial industry architectures.

Robert Prieto Chairman & CEO of Strategic Program Management, and a senior member at National Academy of Construction among other professional organizations. Bob consults with owners of large engineering and construction programs across all market sectors in the development of programmatic delivery strategies encompassing planning, engineering, procurement, construction, and financing.

William B. Rouse is a researcher, educator, author and entrepreneur and a research Professor in the McCourt School of Public Policy at Georgetown University and Professor Emeritus in the School of Industrial and Systems Engineering at the Georgia Institute of Technology. His expertise includes individual and organizational decision making and problem solving, as well as design of complex enterprise and information systems.

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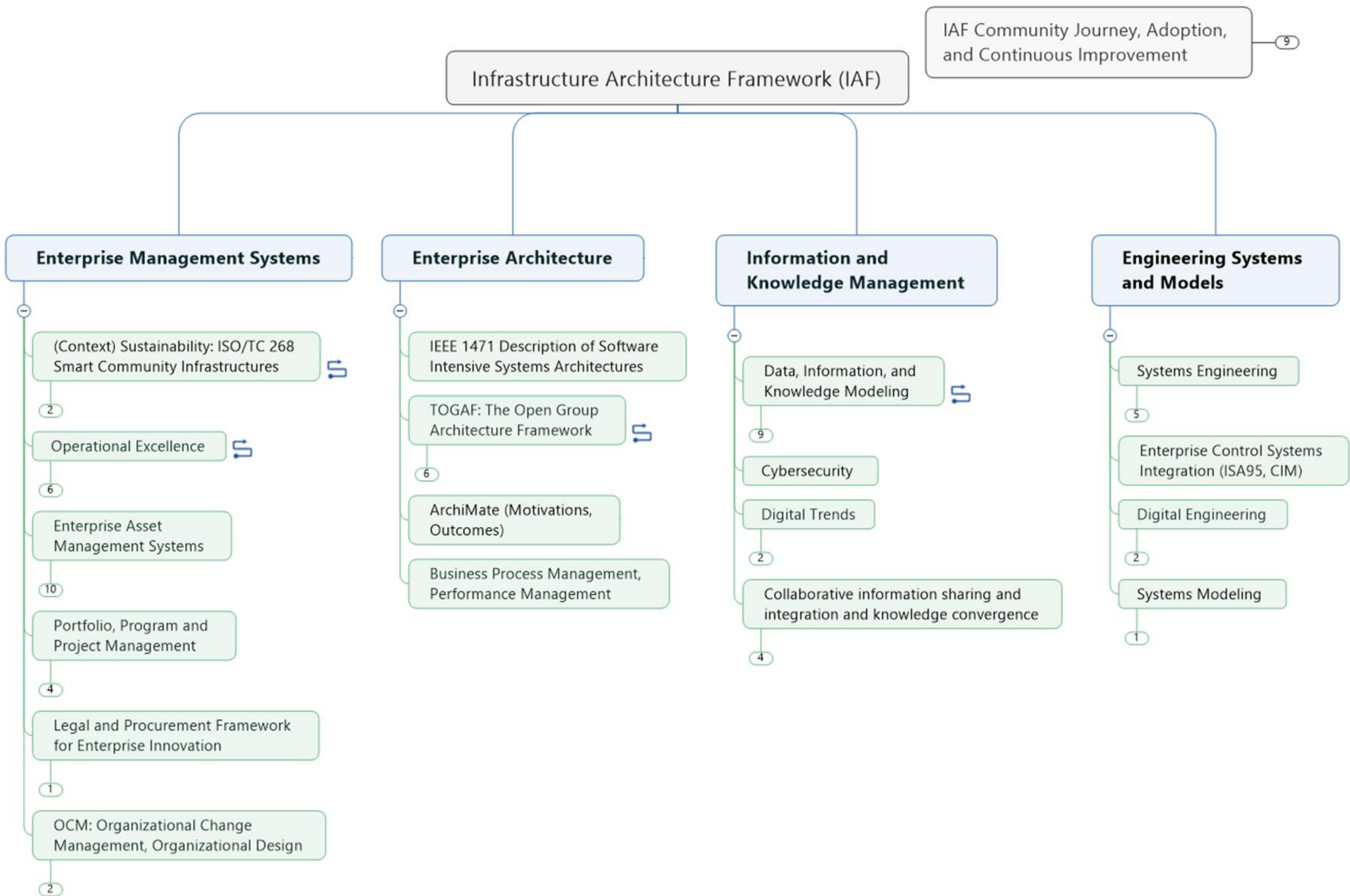
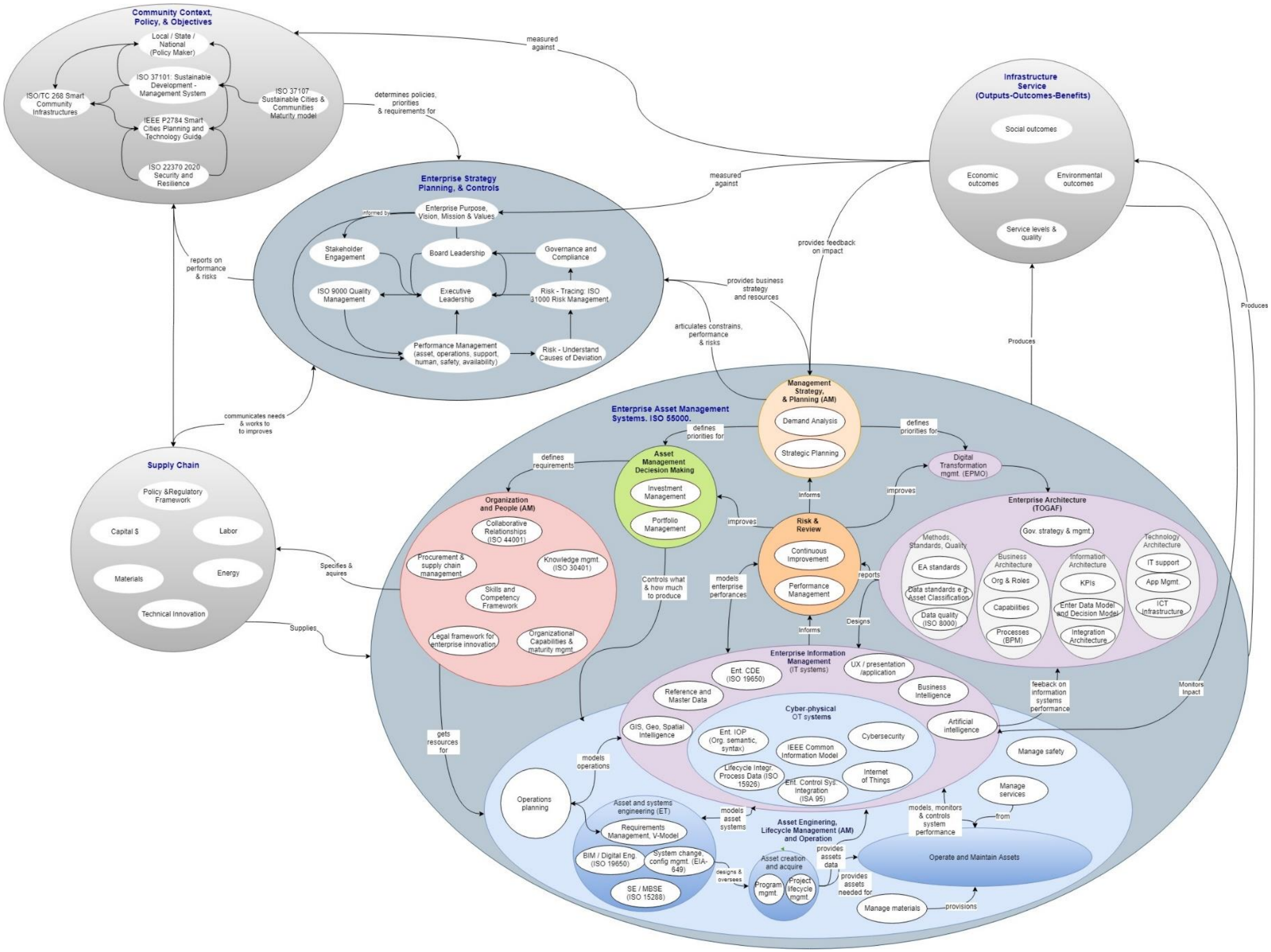
Conceptual Hierarchy Used for the IAF



Systemigram of the IAF



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