Systems Engineering: Historic and Future Challenges

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Humans have faced increasingly complex challenges and have had to think systematically and holistically in order to produce successful responses to these challenges. From these responses, generalists have developed generic principles and practices for replicating success. Some of these principles and practices have contributed to the evolution of systems engineering as a discipline.

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Contents

Historical Perspective

Some of the earliest relevant challenges were in organizing cities. Emerging cities relied on functions such as storing grain and emergency supplies, defending the stores and the city, supporting transportation and trade, providing a water supply, and accommodating palaces, citadels, afterlife preparations, and temples. The considerable holistic planning and organizational skills required to realize these functions were independently developed in the Middle East, Egypt, Asia, and Latin America, as described in Lewis Mumford's *The City in History* (Mumford 1961).

Megacities, and mobile cities for military operations, such as those present in the Roman Empire, emerged next, bringing another wave of challenges and responses. These also spawned generalists and their ideological works, such as Vitruvius and his *Ten Books on Architecture* (Vitruvius: Morgan transl. 1960). "Architecture" in Rome meant not just buildings, but also aqueducts, central heating, surveying, landscaping, and overall planning of cities.

The Industrial Revolution brought another wave of challenges and responses. In the nineteenth century, new holistic thinking and planning went into creating and sustaining transportation systems, including canal, railroad, and metropolitan transit. General treatises, such as *The Economic Theory of the Location of Railroads* (Wellington 1887), appeared in this period. The early twentieth century saw large-scale industrial enterprise engineering, such as the Ford automotive assembly plants, along with treatises like *The Principles of Scientific Management* (Taylor 1911).

The Second World War presented challenges around the complexities of real-time command and control of extremely large multinational land, sea, and air forces and their associated logistics and intelligence functions. The postwar period brought the Cold War and Russian space achievements. The U.S. and its allies responded to these challenges by investing heavily in researching and developing principles, methods, processes, and tools for military defense systems, complemented by initiatives addressing industrial and other governmental systems. Landmark results included the codification of operations research and SE in *Introduction to Operations Research* (Churchman et. al 1957), Warfield (1956), and Goode-Machol (1957) and the Rand Corporation approach as seen in *Efficiency in Government Through Systems Analysis* (McKean 1958). In theories of system behavior and SE, we see cybernetics (Weiner 1948), system dynamics (Forrester 1961), general systems theory (Bertalanffy 1968), and mathematical systems engineering theory (Wymore 1977).

Two further sources of challenge began to emerge in the 1960s and accelerated in the 1970s through the 1990s: awareness of the criticality of the human element, and the growth of software functionality in engineered systems.

Concerning awareness of the human element, the response was a reorientation from traditional SE toward "soft" SE approaches. Traditional hardware-oriented SE

featured sequential processes, pre-specified requirements, functional-hierarchy architectures, mathematics-based solutions, and single-step system development. A Soft Systems approach to SE is characterized by emergent requirements, concurrent definition of requirements and solutions, combinations of layered service-oriented and functional-hierarchy architectures, heuristics-based solutions, and evolutionary system development. Good examples are societal systems (Warfield 1976), soft systems methodology (Checkland 1981), and systems architecting (Rechtin 1991 and Rechtin-Maier 1997). As with Vitruvius, "architecting" in this sense is not confined to producing blueprints from requirements, but instead extends to concurrent work on operational concepts, requirements, structure, and life cycle planning.

The rise of software as a critical element of systems led to the definition of Software Engineering as a closely related discipline to SE. The Systems Engineering and Software Engineering knowledge area in Part 6: Related Disciplines describes how software engineering applies the principles of SE to the life cycle of computational systems (in which any hardware elements form the platform for software functionality) and of the embedded software elements within physical systems.

Evolution of Systems Engineering Challenges

Since 1990, the rapidly increasing scale, dynamism, and vulnerabilities in the systems being engineered have presented ever-greater challenges. The rapid evolution of communication, computer processing, human interface, mobile power storage and other technologies offers efficient interoperability of net-centric products and services, but brings new sources of system vulnerability and obsolescence as new solutions (clouds, social networks, search engines, geo-location services, recommendation services, and electrical grid and industrial control systems) proliferate and compete with each other.

Similarly, assessing and integrating new technologies with increasing rates of change presents further SE challenges. This is happening in such areas as biotechnology, nanotechnology, and combinations of physical and biological entities, mobile networking, social network technology, cooperative autonomous agent technology, massively parallel data processing,

cloud computing, and data mining technology. Ambitious projects to create smart services, smart hospitals, energy grids, and cities are under way. These promise to improve system capabilities and quality of life but carry risks of reliance on immature technologies or on combinations of technologies with incompatible objectives or assumptions. SE is increasingly needed but increasingly challenged in the quest to make future systems scalable, stable, adaptable, and humane.

It is generally recognized that there is no one-size-fits-all life cycle model that works best for these complex system challenges. Many systems engineering practices have evolved in response to this challenge, making use of lean, agile, iterative and evolutionary approaches to provide methods for simultaneously achieving high-effectiveness, high-assurance, resilient, adaptive, and life cycle affordable systems;. The emergence of system of systems (SoS) approaches have also been introduced, in which independent system elements developed and deployed within their own life cycle are brought together to address mission and enterprise needs.

Creating flexible and tailored life cycles and developing solutions using combinations of engineered systems, each with its own life cycle focus, creates its own challenges of life cycle management and control. In response to this, enterprise systems engineering (ESE) approaches have been developed, which consider the enterprise itself as a system to be engineered. Thus, many of the ambitious smart system projects discussed above are being delivered as a program of managed life cycles synchronized against a top down understanding of enterprise needs. It is important that within these approaches we create the flexibility to allow for bottom-up solutions developed by combining open, interoperable system elements to emerge and be integrated into the evolving solutions.

More recently, emerging technologies such as artificial intelligence, machine learning, deep learning, mechatronics, cyberphysical systems, cybersecurity, Internet of Things (IoT), additive manufacturing, digital thread, Factory 4.0, etc. are challenging approaches to SE.

Many of the challenges above, and the SE response to them, increase the breadth and complexity of the systems information being considered. This increases the need for up to date, authoritative and shared models to support life cycle decisions. This has led to the development and ongoing evolution of model-based

systems engineering (MBSE) approaches.

Future Challenges

The INCOSE Systems Engineering Vision 2025 (INCOSE 2014) considers the issues discussed above and from this gives an overview of the likely nature of the systems of the future. This forms the context in which SE will be practiced and give a starting point for considering how SE will need to evolve:

- Future systems will need to respond to an ever growing and diverse spectrum of societal needs in order to create value. Individual engineered system life cycles may still need to respond to an identified stakeholder need and customer time and cost constraint. However, they will also form part of a larger synchronized response to strategic enterprise goals and/or societal challenges. System life cycles will need to be aligned with global trends in industry, economy and society, which will, in turn, influence system needs and expectations.

- Future systems will need to harness the ever-growing body of technology innovations while protecting against unintended consequences. Engineered system products and services need to become smarter, self-organized, sustainable, resource efficient, robust and safe in order to meet stakeholder demands.

- These future systems will need to be engineered by an evolving, diverse workforce which, with increasingly capable tools, can innovate and respond to competitive pressures.

These future challenges change the role of software and people in engineered systems. The Systems Engineering and Software Engineering knowledge area considers the increasing role of software in engineered systems and its impact on SE. In particular, it considers the increasing importance of cyber-physical systems in which technology, software and people play an equally important part in the engineered systems solutions. This requires a SE approach able to understand the impact of different types of technology, and especially the constraints and opportunities of software and human elements, in all aspects of thelife cycle of an engineered system.

All of these challenges, and the SE responses to them,

make it even more important that SE continues its transition to a model-based discipline.

The changes needed to meet these challenges will impact the life cycle processes described in Part 3: Systems Engineering and Management and on the knowledge, skills and attitudes of systems engineers and the ways they are organized to work with other disciplines as discussed in Part 5: Enabling Systems Engineering and Part 6: Related Disciplines. The different ways in which SE is applied to different types of system context, as described in Part 4: Applications of SE, will be a particular focus for further evolution to meet these challenges. The Introduction to SE Transformation knowledge area in SEBoK Part 1 describes how SE is beginning to change to meet these challenges.

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< Previous Article | Parent Article | Next Article >
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