Fundamentals for Digital Engineering

Lead Authors: *Emiliya Suprun, Sondoss Elsawah*

The world has witnessed exponential growth in technological advancement in recent years, and systems engineering (SE) is no exception. SE is transforming the way we design, analyze, and manage complex systems. This transformational change leverages the use of advanced technologies such as Artificial Intelligence (AI), Big Data, and Internet of Things (IoT). However, the evolution of SE goes well beyond just technology advancements. This chapter discusses digital engineering (DE) as a systemic intervention, a holistic approach to SE transformation that involves people, processes, data, and technology.

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Contents

Additional References

INCOSE Vision 2035: Transforming SE

The INCOSE Vision 2035 statement (INCOSE 2021) provides insights into the global context for SE, highlighting key trends and influencing factors expected to drive changes in the practice of SE. Some of the principal takeaways include but are not limited to the impacts of digital transformation:

- Digital transformation, sustainability, smart systems and complexity growth, and advancements in modeling, simulation, and visualization are trends that impact enterprise competitiveness.
- The future SE will leverage digital transformation in its tools and methods and move towards a fully model-based SE environment.
- The changing nature of systems includes more embedded and application software, increasing amounts of data to process, and cyber-physical systems.
- The systems of the future will be engineered by an evolving, diverse workforce reshaped by digital transformation and systems of systems.
- Data science techniques will be infused into the SE practice, with trusted data being managed as a critical asset.
- Digital technology, including the broader application of AI, enables the transformation of how enterprises capture, reuse, exploit, and protect knowledge through digital representation and semantic integration of all information.
- Evolving digital ecosystems will enable automation and autonomy to perform increasingly complex tasks.

All engineering disciplines today have evolved, and modern SE needs to be supported by large amounts of data. This requires the transformation of SE practices to DE in which technological innovations are assembled to allow for an integrated digital approach that supports life cycle activities and develops a culture among stakeholders of working more efficiently and effectively (DoD 2018). DE is not a destination but a journey towards the digital transformation of engineering and enterprises. This journey requires a paradigm shift from a traditional paper-based SE to a more integrated approach that leverages digital technology to accelerate the formalization and integration of knowledge, fostering collaboration and adopting a more agile approach to SE.

What is DE?

DE provides an integrated digital approach that uses authoritative sources of systems data and models as a continuum across disciplines to support lifecycle activities from concept through disposal (DoD, 2018). ABAB (2021) defines DE as a collaborative way of working, using digital processes to enable more productive methods of planning, designing, constructing, operating, and maintaining assets. Collaboration with suppliers and partners is improved through DE, reducing the risk of errors and delays. DE is reshaping the landscape of how capabilities, assets and projects are designed and managed across many industries, including defense, transportation, construction, healthcare delivery, and other sectors. Examples include:

- In the defense sector, DE enables the development of innovative weapon systems, reduction in acquisition timelines and improvement of the force's readiness (Zimmerman et al. 2019).
- In transportation, DE improves the design and optimization of infrastructure systems, such as roads, bridges, and airports, to improve safety and efficiency (Wu et al. 2022). DE drives the improvement of the resilience of critical infrastructure systems, such as power grids, water systems, and transportation networks (Suprun et al. 2022).
- In construction, DE enables the design and construction of smarter and more sustainable buildings and infrastructure and the reduction of construction costs and waste (Opoku et al. 2021).
- In healthcare, DE enables development of new medical devices, optimization of hospital operations, and improvement in patient outcomes (Awad et al. 2021). The list goes on.

DE as a Systemic Intervention in Its Own Right

DE is underpinned by the view of enterprises as sociocultural-technical systems (Sony & Naik, 2020). DE is a systemic intervention that comprises four fundamental components: Why, What, Who and How. These components work together to enable fundamental shifts in organizational culture, practices, and technologies to achieve enterprise digital transformation. Figure 1 provides a holistic view of the dimensions and elements that make the DE intervention.

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Figure 1. Digital Engineering Systemic Framework

Why: Strategic Intent

The *why* component is critical for establishing the goals and objectives of the DE initiative, as well as for ensuring that it aligns with the broader organizational strategy. DE is not exclusively about technology but the fact that technology enables organizations to transform their business operations and systems and create better-informed decisions around their organizational objectives and strategy.

As part of the process, the immediate targets of transforming SE practices include the digitalization of engineering artifacts, information, and model sharing, while the long-term strategic vision is focused on aligning investments into technological innovations and advanced engineering practices with organizational goals and objectives (Huang, 2020). The organizational view of digital transformation opportunities and innovation should be considered as part of a more extensive continuous improvement process.

A clear DE strategy provides a roadmap for digital transformation, outlining the steps needed to achieve organizational outcomes. They should also consider the organization's culture and how DE transformation will impact the workforce as well as its existing systems and processes. A successful strategy involves stakeholder collaboration to ensure buy-in and alignment with the organization's goals and leadership development. DoD DE Strategy (DoD 2018) identifies the following goals that could be applied to DE activities: (i) model use for decision-making; (ii) developing the authoritative source of truth (AST); (iii) enhancing technological innovation; (iv) establishing collaborative environments; and (v) transforming the workforce and cultural.

A systemic approach to DE drives a shift from a technology-focused acquisition approach to a whole ecosystem view that supports all enablers for genuine transformation, including workforce readiness and awareness of the legal and policy environment. Moreover, the strategic view on DE allows organizations to realize the value of data and information. Industries must collectively recognize the importance of valuing and managing data and information as critical assets.

Who: Digitally Enabled Workforce

The *who* component of DE focuses on the workforce. This component is critical for ensuring industries have the necessary skills and capabilities to embark on the DE journey. It involves identifying the skills, roles, responsibilities, and capabilities needed for the successful digital transformation of engineering and enterprises. It is essential to have a digitally enabled workforce trained and capable of using technological innovation to effectively leverage digital tools and methods.

DE requires a new comprehensive set of skills and competencies beyond traditional SE and IT. It requires a combination of technical and specific data management expertise, such as modeling and simulation, data analytics, AI, and cybersecurity, as well as soft skills, such as communication, collaboration, and leadership.

The DE competency framework developed by Hutchison and Tao (2022) identifies the foundational digital competencies: (i) digital literacy; (ii) DE value proposition; (iii) DoD Policy/Guidance; (iv) decision-making; (v) software literacy.

Social and cultural aspects of DE also include the need for a shift in mindset and culture. DE requires a more collaborative agile approach to design, develop, and deploy complex systems and a willingness to adapt and embrace change. It also requires a culture of innovation, continuous improvement and learning as technologies and tools evolve rapidly. The growing worldwide demand for digital and systems engineers exceeds the available supply (INCOSE 2021). Many enterprises initiate internal in-house training programs to develop their workforce further. Nevertheless, there is a need for training and education programs and a life-long learning pipeline that empower more system engineers with strong multi- and transdisciplinary competencies, including digital, business, leadership and systems thinking, needed to enable collaboration across a broad range of the engineering and management workforce globally.

What: Data, Technology, and Knowledge and Perspectives

The *what* component captures dimensions of integration, being data, technology, and knowledge and perspectives. SE faces a significant obstacle today due to the extensive fragmentation among the engineering tools and data landscape (INCOSE 2021). In DE, the use of common integrated models helps overcome these challenges. Integration across different tools, technological solutions and data is becoming a focus for enabling collaboration, analytics, and data-informed decision-making. Integration also ensures that the data generated by different tools are standardized and can be seamlessly shared across different engineering disciplines.

Data is at the heart of DE, and enterprises need to invest in the capabilities for seamless collection, management, and analysis of data to support their digital transformation. Real-time data can improve how complex systems and assets are operated, enable informed decision-making, and allow better responses to disruptions, failures, and environmental concerns. Nevertheless, collecting the trusted data alone is insufficient to improve SE practices. The key is to support an integrated approach enabling the use of high-quality data, security, privacy, and accessibility in a form that allows sharing, visualization, and analysis. For the systems and assets to be managed efficiently, it is crucial to enable consistent, informed decision-making that relies on high-quality, robust data. An organization's insights are only as good as its data. In other words, the value maximization from the physical system requires the value maximization from the data and information. Valuing and managing data and information as critical assets allow a fundamental shift towards data-driven decision-making built on a 'digital by default' culture.

Knowledge is another critical enterprise asset. Both data and knowledge must be managed appropriately for an enterprise to continue to learn and advance. The knowledge and perspectives component of DE encompasses the importance of understanding and sharing common mental models across stakeholders and establishing a shared understanding of DE. Failure to address the underlying cultural shift, a change in mindset, and a new way of thinking will result in "putting a new coat of technological paint over the same crumbling organizational walls" (Forsythe & Rafoth 2022). Hence, DE must be approached as a cultural transformation, where stakeholders across the enterprise are encouraged to adopt new ways of thinking and working together. This requires a top-down commitment to the new approach and investment in training, education, and tools to enable all stakeholders to understand and work within the new paradigm. This shift in mindset and culture can be difficult and requires leadership to drive the change (Laskey et al. 2021).

The technology component is critical for ensuring organizations have the infrastructure, tools, and platforms to support DE. Technology transforms how enterprises capture, reuse, exploit, and protect knowledge through digital representation and semantic integration of all information. Evolving technology, including digital twins, modeling and simulation tools, and data analytics and visualization tools with the broader application of AI, ML, and IoT, will enable automation and autonomy to perform increasingly complex tasks, providing further opportunities for humans to add value through innovation.

The key shift enabled by DE as an integrated approach is a move to collaborative data-driven problem-solving practices. This drives culture transformation and organizational commitment to a 'single source of truth' approach to decision-making.

How: Processes and Systems

The *how* component of DE focuses on processes and systems. As the future of SE, DE is model-based, leveraging next-generation modeling and simulation powered by global digital transformation (INCOSE 2021). The right processes and systems in place provide consistent digital transformation to deliver value throughout system elements, disciplines, the life cycle, and the enterprise. Defined processes and structured procedures ensure that information fits its intended purpose and can be shared and reused. Moreover, organizations must develop a systematic approach to integrate DE tools and techniques into their existing processes and systems to allow for a seamless flow of data, information, knowledge, and expertise.

DE opens new opportunities but also introduces new integration challenges. One of the critical challenges is the need for interoperability and standardization. Standardized or commonly shared digital representation forms, semantics, and vocabulary are critical for sharing digitalized engineering artefacts, especially digital models.

The core concept in DE is using digital models integrated with simulation, multi-disciplinary analysis, and immersive visualization environments. In other words, one of DE's key technical aspects is using model-based systems engineering (MBSE). MBSE provides a common language and framework for communicating and managing system requirements, design, and implementation. MBSE also enables system designers and engineers to simulate and test system behavior in a virtual environment, reducing the need for physical prototypes. The transformation to DE is happening step by step, and the evolution goes beyond just MBSE. While MBSE is a critical component of DE, it is only one part of a more significant shift towards digital transformation (McDermott et al. 2022). DE involves a fundamental shift in mindset and requires organizations to embrace a more collaborative approach to problem-solving, with stakeholders from across the organization working together to develop more efficient, effective, and responsive solutions to rapidly changing industry demands.

The key shift enabled by DE processes and systems is a move towards the end-to-end digital representation of the enterprise to address long-standing challenges associated with complexity, uncertainty, and rapid change in deploying and using systems. DE also drives a shift from confined and ad-hoc use of models for immediate benefits to continuous and coherent use of models across the lifecycle to drive and accelerate organizational outcomes.

Conclusions

DE goes beyond using specific software tools and models. It builds upon the principles of SE, leveraging technologies and modeling and simulation methods to enhance data-driven decision-making and optimize system performance. DE is about creating a culture of innovation, collaborative problem-solving, and continuous improvement, changing how we connect, understand, and navigate our environments.

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< Previous Article | Parent Article | Next Article >
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