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Towards an Enterprise Architecture for a Digital Systems Engineering Ecosystem

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Abstract

The digital transformation era is upon us. Digital transformation gradually crawls up the value chain from services and manufacturing to product design and systems engineering. In this paper we envision a cloud-based ecosystem of systems engineering, which is model-based by definition. The ecosystem model we propose is called 2MIDSTARs, which stands for: Model, Infrastructure, Data Services, Simulation, Testing, Analysis, and Repositories + Management, Interoperability, Digital Representation, System, Technology, Audit, and Reporting. The first MIDSTAR covers the intrinsic, core MBSE capabilities, while the second MIDSTAR facilitates the integration with the digital enterprise that surrounds the digital systems engineering ecosystem. In this paper we explain the importance of jointly considering all these elements together and outline the key roles and functionalities of each component.

Keywords: Digital Transformation, Digital Systems Engineering, Model-Based Systems Engineering

Nomenclature

DSEE	Digital Systems Engineering Ecosystem / Enterprise
IoT	Internet of Things
MBSE	Model-Based Systems Engineering
MIDSTAR(1)	Modeling Services, Infrastructure Services, Data Services, Simulation Services, Testing Services, Analysis Services, Repositories
MIDSTAR(2)	Management Tools, Interoperability Services, Digital Representations, Systems, Things, Auditing, and Reporting Services
OPD	Object-Process Diagram
OPM	Object-Process Methodology

1. Introduction

The digital revolution has been making an impact on everyday lives across various service-oriented ecosystems over the past decade. Coupled with the fourth industrial revolution – Industry 4.0, and the growing presence of the Internet of Things (IoT), the digital transformation is making its way up the value chain, from advanced manufacturing through product design to systems engineering and business management (Ustundag and Cevikcan, 2018).

Model-based systems engineering (MBSE) adoption and utilization have been constantly growing over the past decade as well (Madni and Sievers, 2018). Model-based system specifications and design decisions are recorded in conceptual models defined in formal or semi-formal modeling languages with a common database. Until recently, it has been consistently regarded as a possibly-better way of conducting systems engineering, as opposed to the document-based approach, but more difficult to implement. The debate has been going on for two decades, with the MBSE supporters growing in numbers but still far behind the masses who still use word processors and electronic worksheets, or the slightly more scalable but still text-intensive requirement management database tools (Cameron and Adsit, 2018). A recent cross-industry survey of MBSE maturity and adoption shows that MBSE is still perceived as immature on the one hand, but as a critical enabler of digital transformation in research & development into a "Digital Engineering" paradigm, on the other hand (McDermott et al., 2020).

It appears that the scene is set for a major transformation in the way systems engineering is done, communicated, and integrated with other business activities, in many ways a rebirth of the engineering systems paradigm (Crawley et al., 2004). However, while systems engineers are poised to be the leading change agents in socio-technical organizations, there is also a risk to the continuity and viability of systems engineering itself (Peterson, 2019). It will no longer be a privilege to use MBSE tools to build and deliver models of complex systems, generate documentation and code, or sync with requirements databases. We believe that systems engineering will need to reinvent itself as a fully digital and integrated business activity. Otherwise, systems engineers will not be able to comply with the digital enterprise strategy (Matt et al., 2015) or the digital enterprise architecture (Goerzig and Bauernhansl, 2018). They will fail to catch up with the velocity of the enterprise, and gradually become irrelevant or unnecessary.

This paper proposes a systems-thinking approach to tackle our concern for the relevance of systems engineering in the digital era. We should begin with understanding what the digital era involves, and what it means for organizations to undergo a digital transformation. Market research has shown that 87% of industries are adopting at least one transformative technology, such as IoT, Artificial Intelligence (AI), Blockchain, or 5G (the next generation of cellular communication) (Builta et al., 2019). An extended yet non-exhaustive list of digital transformation technologies is illustrated in Figure 1.

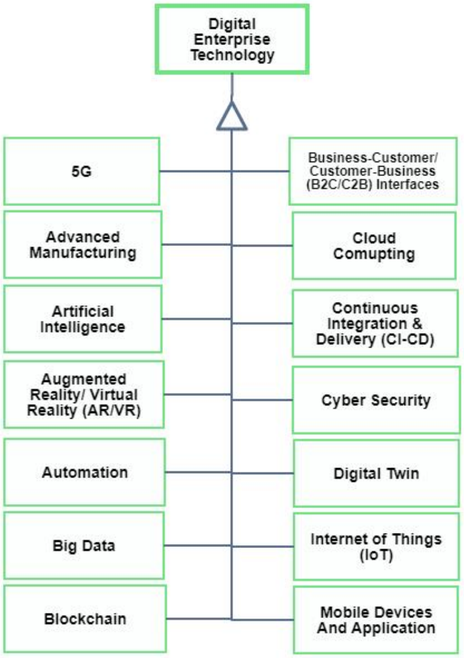

Figure 1. Digital Enterprise Technology enabling and driving the Digital Transformation in socio-technical organizations

Many organizations seeking to undergo a digital transformation – including defense and government agencies, industrial and commercial enterprises, energy facilities, software and hardware manufacturers, and service providers – may be tempted to purchase a few commercial off-the-shelf (COTS) solutions, possibly with the assistance of a consultant to accompany the process. These organizations may not be aware of the need to define the Concept of Operations for the enterprise that will utilize the capabilities of the digital ecosystem, and the Operational Concept that will characterize the activity of the constituent services.

For instance, imagine a factory that shifts to automated manufacturing based on quickly generated product and part design files, that are automatically retrieved and provided to stations along the assembly line or supply chain. If the product and part designers have not been trained with design-to-manufacture techniques and tools, and the factory did not integrate the computer aided design (CAD), product lifecycle management (PLM), and enterprise resource management (ERM) systems – this digital transformation is bound to fail.

Several approaches to reimagine systems engineering as a digital practice have been suggested, for instance through a Zachman Framework with various model layers, agile management, and novel software development and delivery practices (e.g. microservices) (Bondar et al., 2017).

NASA undertook a Digital model-based Systems Engineering (DMBSE) study to gain better understanding of expectations and challenges associated with such a digital transformation (Hale et al., 2017). NASA's report defined Digital model-based Engineering (DMbE) as the use of digital artifacts, digital environments, and digital tools in the engineering process – as opposed to the traditional documentation-based engineering methods. The NASA team identified several key stakeholder expectations. A set of stakeholder requirements for the digital ecosystem, is illustrated in Figure 2.

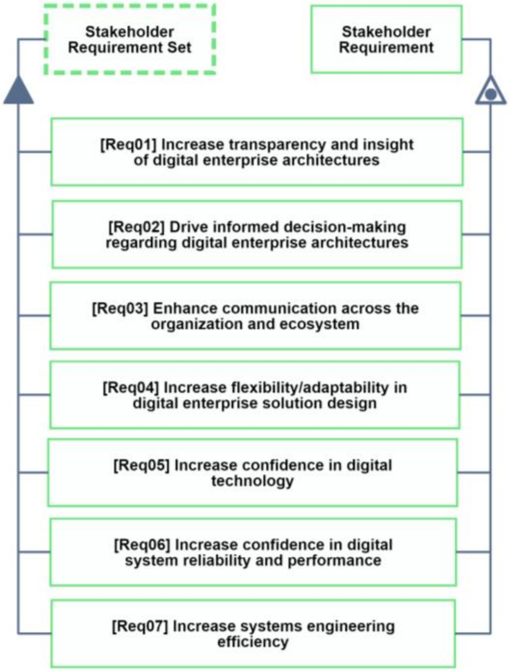

Figure 2. Stakeholder Requirements for the Digital Systems Engineering Ecosystem as an enabler of Digital Transformation

NASA's workgroup also identified several challenges: assessing added value, overcoming organizations culture barriers, regulating the contractual deliverables to meet the standard, building a supporting information technology infrastructure, and ensuring cyber-security.

Additional concerns, mentioned by an anonymous reviewer of this paper, are the setup cost, the challenge of dealing with legacy processes and artifacts, and assuring stakeholders that emerging frameworks will be comprehensive, and that they will be viable and deliver return on investment (RoI).

Another ongoing study (Bone et al., 2018; Hagedorn et al., 2020) looked into semantic and ontological integration of models as an enabler for information sharing and collaboration across R&D ecosystems, involving multiple types of models, multiple analysis tools, and multiple data and information consumers.

2. The Digital Systems Engineering Ecosystem

We propose an enterprise architecture for a digital systems engineering ecosystem (DSEE). The architecture has been conceived in order to capture the most relevant aspects of the DSEE: the stakeholders, the core function and purpose of this ecosystem, and the primary constituent systems in this architecture – aligning to the systems architecting process we would have conducted for any system (Crawley et al., 2015).

The proposed enterprise architecture that supports and enables the DSEE is called 2MIDSTARs, a shorthand version of two MIDSTAR acronyms, each consisting of different items. The constituent systems in this architecture are, in the order of appearance in the acronym: Modeling Services, Infrastructure Services, Data Services, Simulation Services, Testing Services, Analysis Services, Repositories (MIDSTAR_1) as well as Management Tools, Interoperability Services, Digital Representations, Systems, Things, Auditing, and Reporting Services (MIDSTAR_2).

The two MIDSTARs are not grouped together by happenstance, but according to a clear separation of the internal environment (MIDSTAR_1) and the external environment (MIDSTAR_2). Thus, MIDSTAR_1 includes functionalities that are integral and central to a model-based systems engineering discipline. MIDSTAR_2 concerns the functionalities that are critical for integrating the digital systems engineering services with the digital enterprise as a whole, and includes upstream, downstream, and lateral integration and interaction.

3. Object-Process Methodology

OPM is a conceptual modeling language and model-based systems engineering paradigm for complex and dynamic systems and processes. OPM was standardized as ISO 19450 (Dori, 2016; *ISO 19450 Automation systems and integration — Object-Process Methodology*, 2015). OPM relies on the minimal universal ontology principle, whereby stateful objects (things that exist), processes (things that occur), and relations among them constitute a necessary and sufficient ontology for describing any conceivable system in the universe (Dori, 2016). OPM's lightweight vocabulary includes ~20 terms.

OPM is visual and textual at the same time. The visual representation is a set of Object-Process Diagrams (OPDs), which are organized hierarchically. OPDs at all levels of the hierarchy retain and allow the same symbol notation, which makes it highly-consistent at all decomposition levels. Thus, OPM has only one kind of diagram. Structural, procedural, and functional aspects can reside jointly or exclusively within any OPD. Processes are represented by ellipses, objects by rectangles, and object states by rountangles inside the object rectangle. Objects and processes can be either informatical or physical, and either systemic or environmental (external to the boundaries of the system). Links express static and dynamic relations.

OPM's textual representation consists of sentences in Object-Process Language, OPL – a subset of English. Each sentence corresponds to an OPD construct – a set of linked things or states – and vice versa. Each OPD is accompanied by an OPD Specification (OPS) – a set of machine-readable OPL sentences.

There are two software tools for creating OPM models: OPCAT and OPCloud. OPCAT (Dori et al., 2010) is a freely available desktop tool with built-in simulation capabilities, which has been used by thousands of academic and professional users around the world and utilized in hundreds of scientific papers over the last two decades, however it is based on obsolete desktop software technology, and its development has ended. It can still be downloaded at http://esml.iem.technion.ac.il. OPCloud (Dori et al., 2018) is a relatively new cloud-based modeling studio (accessible on-line at https://opcloud-trial.firebaseapp.com/), which is under continuous development and evaluation. OPCloud has already been shown to be useful for various domains including medicine (Levi-Soskin et al., 2019), industry (Dori et al., 2020), and enterprise/aerospace architectures (Mordecai et al., 2020). In this paper, we use OPCloud as a modeling tool and framework – which makes perfect sense, since cloud-based capabilities are of utmost importance for such a digital MBSE environment.

4. An Enterprise Architecture of Two MIDSTARs

As explained, the architecture consists of two layers – internal and external. The internal layer consists of all services that make a holistic MBSE environment for the organization. While MBSE focuses on modeling the systems of interest, we extend this scope to cover additional services that we believe are critical for a true MBSE environment, which delivers value to systems engineers and systems engineering stakeholders.

The external layer transforms the MBSE architecture into a digital one, and aligns with the digital enterprise as a whole. This layer facilitates interactions with the operational domain that the MBSE focuses on. In a digital world, a model-based design of a critical process can interact with the actual operational enablers or facilitators of that process. The interaction may be possible in both ways: the system of interest and its components are able to consult the model to build machine perception of the process, but also to update configurations and deployments according to revised model structures.

In addition to interacting with the operational domain, the external layer also allows the DSEE to interact with the rest of the digital enterprise for sharing information, dictating solutions, or requesting resources. The architecture should be cloud-based but this is not mandatory. Utilizing lightweight and easy-to-adjust web services and interfaces that run in or through the cloud will result in significant productivity, streamlining, and synergy. It will also allow for integration with and preservation of legacy assets and reduce transition costs.

Even if the organization is classified or disconnected from the internet for other reasons, it will be essential for the organization to build a digital laboratory that will allow the enterprise to take advantage of cloud services and adjust them to the needs and challenges of the deployment in question. With commercially available cloud stack packages, this is doable and has been practiced by several classified organizations or sub-organizations in the defense, homeland security, healthcare, finance, and energy domains.

Figure 3 shows the DSEE, the main groups of stakeholders: systems engineers, the systems engineering research community, and the systems engineering software vendors. They all have in common the purpose of generating value in the form of digital systems engineering deliverables: models, tradespace analyses, functional requirements, validation and verification reports, performance assessments, etc. The stakeholder requirements and digital enterprise technologies are both represented as packages that unfold in separate diagrams. The 2MIDSTARs architecture as a collection of services enables the DSEE. The components of MIDSTAR$_1$ and MIDSTAR$_2$ are listed in Table 1 and Table 2, respectively.

Several architectural principles are implemented in this architecture:

- **Distributed Data Flow**: all the data is expected to be shared via a central data distribution service, which is part of the Infrastructure. This allows for multiple entities of the same type to connect and exchange data with each other, it allows easier virtualization and eliminated interdependency as found in direct interfaces.
- **Expertise**: as opposed to various MBSE platforms which may include a subset of the required capabilities, this architecture advocates isolation and separation of services. These services may still share common user interfaces and other common resources, but the ability to mix and match various software technologies to form an optimal DSEE is essential and more important than a single interface.
- **Focus on Core Competence**: the core MBSE competence includes modeling, simulation, and analysis services, along with supporting data management, access, and storage services. Tools that are available in the software market with expertise in their domain, such as project and task management tools, configuration control and auditing, or dashboards and visualization software – all do a better job in their area and will better serve the ecosystem than localized developments of similar capabilities.
- **Scalability and Extendibility**: the architecture is built to allow further extension and enhancement for upscaling and broader digital scopes. While this concern is currently beyond the scope of this study, it remains important to ensure this degree of freedom for future enhancements.

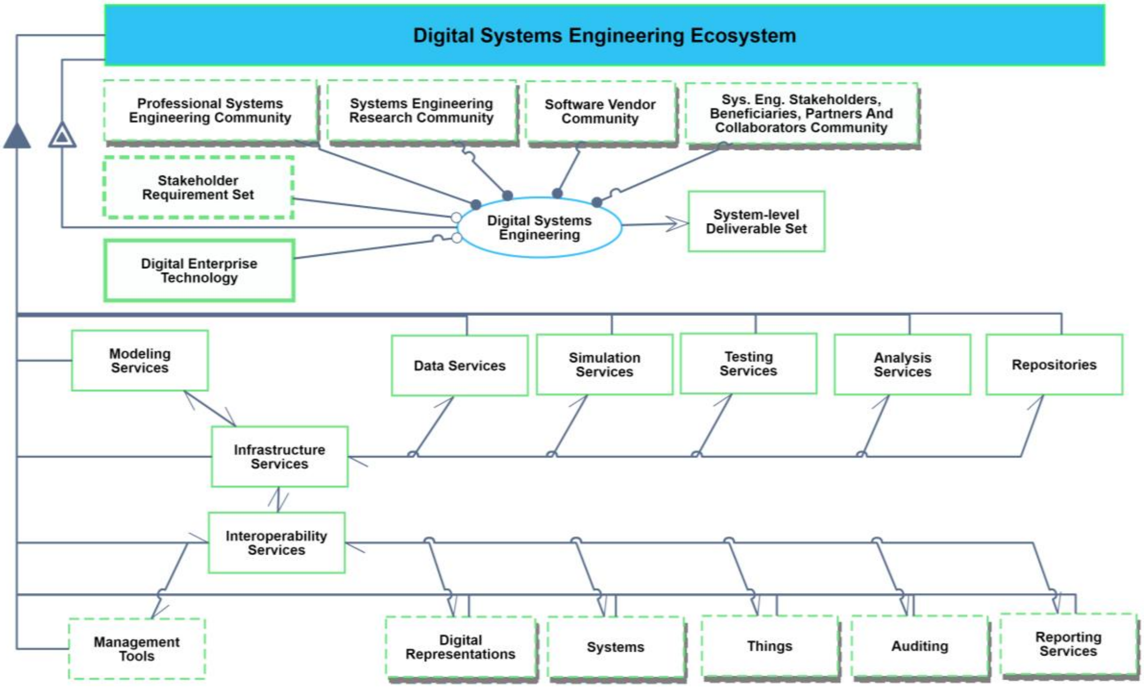

Figure 3. The 2MIDSTARs enterprise architecture of the Digital Systems Engineering Enterprise clearly shows the two layers of services that make up the Digital Systems Engineering Ecosystem: the upper, internal layer (MIDSTAR$_1$) and lower, external layer (MIDSTAR$_2$).

Table 1. MIDSTAR$_1$: Internal MBSE Layer

Services	Purpose
Modeling Services	Build, store, and visualize models in a variety of modeling languages
Infrastructure Services	Facilitate interaction among MIDSTAR1 components, and with MIDSTAR2's gateway, provide security and IT governance
Data Services	Distribute and retrieve data: enterprise datasets to inform models, model-generated data, application data and model metadata
Simulation	Validate and verify system model
Testing Services	Connect with test platforms, generate tests in compliance with the models
Analysis Services	Analyze, summarize, and validate data, deliver additional value-added capabilities based on the models and simulation results
Repositories	Store and access information of various sorts, including models, analysis results, test plans and results, simulation threads and results, and raw data sources

Table 2. MIDSTAR$_2$: External DSEE Enabler

Services	Purpose
Management Tool	Integrate with standard organization management tools to control DSEE activity
Interoperability Services	Interact with MIDSTAR$_1$ through its gateway, and among MIDSTAR$_2$ members
Digital Representation	Build or use digital representations, including engineering designs, software code, digital twins, and virtual environments
System	Deployed realization of a model; interacts with the model that represents it
Thing	Connected entity that models can interact with: sensors, actuators, controllers, energy/signal emitters, etc.
Audit	Organizational services that audit activity and ensure viability, quality, transparency, legality, regulation compliance, governance.
Reporting	Generate textual, tabular, graphical, visual, and multimedia representations of model information; communicate MBSE outputs and deliverables across the ecosystem

5. Discussion

This paper presents a high-level enterprise architecture for a Digital Systems Engineering Ecosystem. By using OPM as a modeling language and the new OPM modeling tool OPCloud as a modeling vehicle, we were able to make the first step of modeling the DSEE using cloud-based tools. Although this is a preliminary model, it serves as a good starting point, capturing core aspects, drawing a clear separation of MBSE core activities from digital interfaces, and clarifying the expertise of each service. We set out with seven stakeholder requirements that the DSEE should tackle. In Table 3 we reflect on the framework's fulfilling (or advances towards fulfilling) of the requirements. This reflection must be fully validated through stakeholder assessment, but it provides a good initial validation for stakeholder focus.

Future research will focus on three directions. First, we plan to extend the architecture to get a better understanding of the microservices required for each service, e.g., what kinds of analysis methods should be included in a model analyzer. This direction will address essential questions that may have naturally arisen on the implementation of proposed constructs, but were beyond the scope of the present paper. In addition, we currently define the data transformation protocols that will allow this transformation to take place. This includes the adoption of mathematical concepts from Category Theory, which has been mentioned as a potential candidate for a foundational theory of Systems Engineering, and for a holistic systems engineering platform, of the kind or essence proposed in this paper (Breiner et al., 2017). Finally, we have begun planting the seeds for such a platform for early-adopter government, industry, and research enterprises. The way such organizations can work in a holistic, cloud-based ecosystem, must also be explored.

Table 3. Fulfilling of Stakeholder Requirements using the DSEE – 2MIDSTARs architecture

Stakeholder requirement	**Fulfilled by…**
1. Increase transparency and insight of digital enterprise architectures.	formulation of this reference framework, which informs stakeholders, decision-makers, professionals, and researchers, and serves as common ground.
2. Drive informed decision-making regarding digital enterprise architectures.	formulation of this reference framework as the basis for framing decisions in all levels (strategic, tactical, operational) in the context of the critical enablers.
3. Enhance communication across the organization and ecosystem.	facilitation of mechanisms for enterprise interoperability.
4. Increase flexibility/adaptability in digital enterprise solution design.	definition of robust entities and services that can be adapted and shaped gradually, according to evolving needs.
5. Increase confidence in digital technology.	referencing of digital enterprise technology agents as enablers of digital transformation at both the enterprise level and the systems engineering level
6. Increase confidence in digital system reliability and performance.	inclusion of internal mechanisms for simulation, testing, and analysis, as well as external mechanisms for auditing and reporting
7. Increase systems engineering efficiency.	formulation of this reference framework which saves time and effort figuring out the issues, and allows for prioritization and road-mapping

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References

Bondar, S., Hsu, J.C., Pfouga, A., Stjepandić, J., 2017. Agile digital transformation of System-of-Systems architecture models using Zachman framework. J. Ind. Inf. Integr. 7, 33–43. https://doi.org/10.1016/j.jii.2017.03.001

Bone, M., Blackburn, M., Kruse, B., Dzielski, J., Hagedorn, T., Grosse, I., 2018. Toward an Interoperability and Integration Framework to Enable Digital Thread. Systems 6, 46. https://doi.org/10.3390/systems6040046

Breiner, S., Subrahmanian, E., Jones, A., 2017. Categorical foundations for system engineering, in: 15th Annual Conference on Systems Engineering Research. https://doi.org/10.1007/978-3-319-62217-0

Builta, J., Howell, J., Ambroggi, L. De, Short, M., Grossner, C., Morelli, B., Tait, D., Hall, T., 2019. Digital Orbit - Tracking the development, impact, and disruption caused by transformative technologies across key industries.

Cameron, B., Adsit, D.M., 2018. Model-Based Systems Engineering Uptake in Engineering Practice. IEEE Trans. Eng. Manag. 67, 152–162. https://doi.org/10.1109/TEM.2018.2863041

Crawley, E., Cameron, B., Selva, D., 2015. Systems Architecture: Strategy and Product Development for Complex Systems. Prentice Hall.

Crawley, E., De-Weck, O., Eppinger, S., Magee, C., Moses, J., Seering, W., Schindall, J., Wallace, D., Whitney, D., 2004. Engineering Systems Monograph - The Influence of Architecture in Engineering Systems.

Dori, D., 2016. Model-Based Systems Engineering with OPM and SysML, Springer. https://doi.org/10.1007/978-1-4939-3295-5

Dori, D., Jbara, A., Levi, N., Wengrowicz, N., 2018. Object-Process Methodology, OPM ISO 19450 – OPCloud and the Evolution of OPM Modeling Tools. Syst. Eng. Newsl. (PPI SyEN) 61, 6–17.

Dori, D., Kohen, H., Jbara, A., Wengrowicz, N., Lavi, R., Natali Levi Soskin, Bernstein, K., Shani, U., 2020. OPCloud: An OPM Integrated Conceptual-Executable Modeling Environment for Industry 4.0, in: Kenett, R.S., Swarz, R.S., Zonnenshain, A. (Eds.), Systems Engineering in the Fourth Industrial Revolution: Big Data, Novel Technologies, and Modern Systems Engineering. Wiley.

Dori, D., Linchevski, C., Manor, R., 2010. OPCAT – An Object-Process CASE Tool for OPM-Based Conceptual Modelling, in: Heisig, P., Clarkson, J., and Vajna, S. (Ed.), 1st International Conference on Modelling and Management of Engineering Processes. University of Cambridge, Cambridge, UK, 19-20 July, pp. 1–30.

Goerzig, D., Bauernhansl, T., 2018. Enterprise Architectures for the Digital Transformation in Small and Medium-sized Enterprises. Procedia CIRP 67, 540–545. https://doi.org/10.1016/j.procir.2017.12.257

Hagedorn, T., Bone, M., Kruse, B., Grosse, I., Blackburn, M., 2020. Knowledge Representation with Ontologies and Semantic Web Technologies to Promote Augmented and Artificial Intelligence in Systems Engineering. Insight 23, 15–20. https://doi.org/10.1002/inst.12279

Hale, J.P., Zimmerman, P., Kukkala, G., Guerrero, J., Kobryn, P., Puchek, B., Bisconti, M., Baldwin, C., Mulpuri, M., 2017. Digital Model-based Engineering: Expectations , Prerequisites , and Challenges of Infusion.

ISO 19450 Automation systems and integration — Object-Process Methodology, 2015. . International Organization for Standardization (ISO), Geneva, Switzerland.

Levi-Soskin, N., Shaoul, R., Kohen, H., Jbara, A., Dori, D., 2019. Model-Based Diagnosis with FTTell: Assessing the Potential for Pediatric Failure to Thrive (FTT) During the Perinatal Stage, in: Wrycza, S., Maślankowski, J. (Eds.), SIGSAND/PLAIS, LNBIP 359. Springer Nature Switzerland AG, pp. 37–47. https://doi.org/10.1007/978-3-030-29608-7_4

Madni, A.M., Sievers, M., 2018. Model-based systems engineering: Motivation, current status, and research opportunities. Syst. Eng. 21, 172–190. https://doi.org/10.1002/sys.21438

Matt, C., Hess, T., Benlian, A., 2015. Digital Transformation Strategies. Bus. Inf. Syst. Eng. 57, 339–343. https://doi.org/10.1007/s12599-015-0401-5

McDermott, T.A., Hutchinson, N., Clifford, M., Van Aken, E., Slado, A., Henderson, K., 2020. Benchmarking the Benefits and Current Maturity of Model-Based Systems Engineering across the Enterprise.

Mordecai, Y., James, N.K., Crawley, E.F., 2020. An Object-Process Model-Based Operational Viewpoint Specification Framework for Aerospace Architectures, in: IEEE Aerospace Conference. IEEE.

Peterson, T.A., 2019. Systems Engineering: Transforming Digital Transformation. INCOSE Int. Symp. 29, 434–447. https://doi.org/10.1002/j.2334-5837.2019.00613.x

Ustundag, A., Cevikcan, E., 2018. Industry 4.0: Managing The Digital Transformation, Springer Series in Advanced Manufacturing. https://doi.org/10.1007/978-3-319-57870-5