23rd Annual Conference on Systems Engineering Research
Intelligent Digital Twin-enabled Systems Engineering for 21st Century Sociotechnical Systems

Editors: Dr. Mathew Amissah[1], Dr. Abbas Zaidi[1], Dr. Ali K. Raz[1], Dr. John Shortle[1], Dr. Azad M. Madni[2], Dr. Dinesh Verma[3],
[1]George Mason University,[2]University of Southern California, [3]Stevens Institute of Technology,

Arlington, VA, USA April 6-9, 2026

Sociotechnical digital twins: The tangibility issue

Prof. Guy André Boy[a], INCOSE Fellow
[a]ESTIA Institute of Technology, g.boy@estia.fr

Abstract

Digital twin technology has numerous applications, including design support for collaborative systems engineering, interactive documentation to maintain constant traceability of design decisions, and suggestive tools for innovation, as well as studies on human and organizational factors throughout the entire life cycle of a sociotechnical system (STS). This paper highlights tangibility as an emergent issue in human systems integration (HSI) and as a guidance provider in the analysis, design, and evaluation of sociotechnical digital twins. Indeed, a digital twin is a virtual entity that warrants investigation of its physical and cognitive (figurative) tangibility. This investigation enables the exploration of the physical and cognitive dimensions of the STS being developed under an Industry 4.0 approach (i.e., utilizing digital engineering), as well as the socio-cognitive factors that emerge from observing and analyzing, in concert, technology, organization, and people in human-in-the-loop simulations throughout the STS life cycle (especially very early at design time). This paper explains how tangibility can be tested and assessed, and how emerging phenomena can be discovered through iterative tests of sociotechnical digital twins. Examples are drawn from several industrial research projects, including the design of a future air combat system, the robotization of oil and gas drilling platforms, the development of a virtual air traffic management tower, and the automation of railways.

Keywords: digital twin; sociotechnical systems; tangibility; digital engineering; human systems integration.

Nomenclature

AI	Artificial intelligence
BPMN	Business Process Modeling and Notations
HAT	Human-AI teaming
HCD	Human-centered design
HITLS	Human-in-the-loop simulation
HSI	Human Systems Integration
MB-HSI	Model-based human systems integration
MBSE	Model-based systems engineering
SDT	Sociotechnical digital twin
STS	Sociotechnical system

1. Introduction

This position paper is based on substantial experience in human systems integration (HSI) of sociotechnical systems (STSs). The corresponding field has recently been presented by a panel of experts [1]. Sociotechnical digital twins (SDTs) emerged as a concept that requires clarification. More specifically, let us present an introductory account of the tangibility issue and guidance for the analysis, design, and evaluation of SDTs. Indeed, SDTs are virtual entities that enable the simulation of STS models. Physical tangibility refers to an object that can be physically grasped (e.g., grabbing a hammer with your hand). Figurative tangibility refers to a concept, an abstraction, or an idea that you grasp with your mind (e.g., when you say, I grasp this idea, you mean you understand it). In digital engineering, these two facets of tangibility have become crucial since the beginning of the 21st century, when we inverted the way that we approach engineering. Let me explain.

Until the end of the 20th century, engineers designed and developed physical things first. Mechanical engineering was about drawing, cutting, and assembling hardware. Everything was graspable physically. Software was introduced second, for example, to automate hardware. During the last decades of the 20th century, engineering transitioned from hardware to software. For instance, we cannot fix our car's engine ourselves today; instead, we need to take it to the shop to diagnose it, and we are immediately informed of the repair cost and the estimated time to complete the work. Since the beginning of the 21st century, everything has started using software at design time. We design a PowerPoint mock-up of the targeted system, develop a concept model, and run a human-in-the-loop simulation (HITLS). Therefore, we can quickly identify practical operational concepts by analyzing emergent activities and immediately redesign the system. We can even 3D-print virtual prototypes of hardware. We are going from software to hardware. Digital engineering operates in a virtual world that we need to make tangible, both physically and figuratively. Digital twins provide the concrete support for this digital modelling and simulation approach, which must be human- and organization-centered for effective STS development.

From a human and organizational factors perspective, this drastic change presents tremendous benefits and new challenges. On the positive side, digital engineering associated with HITLSs (i.e., based on digital twins) enables the consideration of human and organizational factors from the very beginning of the design and development process. In addition to task analysis (i.e., analysis of what is prescribed), activity analysis (i.e., analysis of what is effectively performed) is now possible at design time. This capability was previously impossible until recently. Human factors specialists discussed "automation surprises" during operational times. Today, we can uncover such surprises at design time and gain a deeper understanding of emerging behaviors and phenomena, which can inform design decisions and further development. On the evolutionary side, digital engineering offers virtual solutions that need to be tested against tangibility metrics. This means the concept of tangibility must be clearly defined, and tangibility metrics must be appropriately developed.

This article proposes a categorization of SDTs based on their association with tangibility attributes for sociotechnical systems (i.e., systems that describe technology, organizations, and people, and their relationships). SDT tangibility is defined as the physical and figurative distance to the real twin. A focus on human-AI teaming will be provided based on a systemic cognition representation. The PRODEC method [2], which associates procedural scenarios with declarative configurations, will be described and illustrated with several examples from industry. Incrementally refined digital twins support PRODEC. A discussion will be initiated, and various perspectives will be shared.

2. Sociotechnical digital twins: What do we really mean?

This paper aims to promote the idea that digital twins are not merely a matter of technology but should be viewed as conceptual and concrete tools that lead to effective HSI, integrating systems engineering with human-centered and organization-centered design and operational support. HSI is the ultimate evolution of human factors and ergonomics, which began after World War II, and human-computer interaction emerged during the 1980s. This evolution resulted from the increase in complexity of sociotechnical systems. Sociotechnical digital twins should be helpful and usable throughout the entire life cycle of an STS, as they offer significant support for anticipation, preparation, creativity, and experience feedback management. They serve as mediating tools for collaborative design, supporting flexibility and adaptability [3]. They enable illustrating what is intended to be developed and what needs to be reported after tests for traceability purposes (i.e., digital twins are unique tools for actively documenting design and its solutions). They can be helpful for "what-if" testing, supporting experience feedback, and facilitating supervised learning.

A sociotechnical digital twin (SDT) can be defined as "a dynamic representation of a physical system using interconnected data, models, and processes to enable access to knowledge of past, present, and future states to manage action on that system" [4]. SDTs can be considered extensions of models used in model-based systems engineering (MBSE) for HSI. MBSE is extended to model-based human systems integration (MB-HSI) [5]. They dynamically and interactively document the design process and the solutions developed, as well as those not chosen (i.e., an active documentation that represents, simulates, and communicates on the system, providing traceability). They support human-in-the-loop simulation (Virtual HCD) for eliciting emerging behaviors and phenomena.

Sociotechnical digital twins involve concurrent engineering of technology, organization, and people [6]. We do not design people; instead, we design jobs and competencies that produce new activities. Whenever we create a new technology or adapt an existing one, the corresponding organizations and individuals involved need to change and adapt. SDTs are mandatory tools to support human-centered design and, consequently, human systems integration, because they enable considering what is actually performed (the activity) at design time, rather than just what is prescribed (i.e., tasks). From a human factors and ergonomics perspective, this is a revolution in engineering practice. Since the beginning of the 21st century, digital engineering has given rise to a new concept and issue: the tangibility of digital experiences.

3. Categorization of sociotechnical digital twins: A Human Systems Integration Approach

The following SDT categorization was developed to better understand what a digital twin can bring to the design, development, operations, and maintenance of STSs (Figure 1).

- First, predictive and explanatory SDTs should be distinguished. The former are typically very well-tested digital analogs of the real-world twin, simple and defined in a limited context, with a short-term focus, rigidity, and a narrow scope. The latter are represented by a domain ontology, which is long-term, flexible, and generic, developed for the analysis, design, and evaluation of STSs, and typically used for documentation purposes. Generally, from an AI perspective, predictive SDTs are based on statistical models, while explanatory SDTs are symbolic, grounded in logic.
- Second, since an SDT is a system, it can be represented as a function and a structure, specifically a function of functions and a structure of structures. SDT structure and function should be clearly defined. Additionally, each structure is typically visualized, and each function is assigned to a specific structure.
- Third, SDTs can be technology-centered or human-centered. This distinction is crucial when discussing a sociotechnical SDT. Technology-centered SDTs are technical models of physical systems. They do not involve people and organizations of the sociotechnical system at stake. Human-centered DTs should be developed to incorporate experience feedback information through clearly defined learning mechanisms incrementally. They can also be used to support the performance of the corresponding sociotechnical systems. They can be helpful in both system design and operations. They support logistics along the whole life cycle of a system. More specifically, they need to support traceability of design decisions, potential redesign, sociotechnical history, and integrated logistics.
- Fourth, the distinction between static and dynamic SDTs is essential. In MBSE, models are static and do not provide a vivid account of the system being described, except through a mental simulation. Dynamic SDTs provide a concrete digital simulation, a kind of active documentation that supports virtual HCD. Not only can they provide support to HITLS, but they can also be improved from experience along the system's life cycle. This kind of learning is usually supervised (i.e., not direct machine learning).
- Fifth, discount SDTs are based on simplified models and simulations. They support practical design thinking. They provide vision support and facilitate mediation between design team members, primarily through human-in-the-loop simulations, subsequent analysis of generated activity, and discovery of emergent behaviors and phenomena. They are good support for creativity and agile development. Finally, they provide appropriate support for documenting modifications and validation of the systems being developed.
- Sixth, full SDTs are the ultimate tools for formative evaluation in iterative, complex design and development processes. They can be successfully used in scenario-based design, where scenarios require fine-grained investigations. At the end of the design process, full SDTs conduct summative evaluations to validate and certify the sociotechnical system being considered. They are helpful throughout the entire life cycle of an STS, particularly in supporting operations for performance assessment and maintenance.

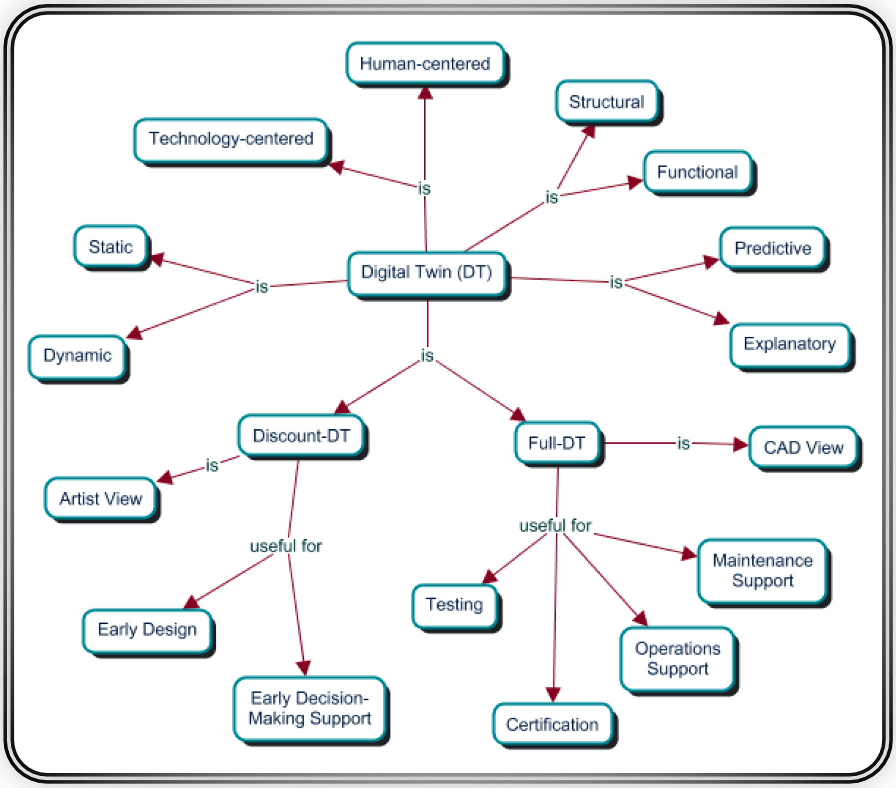

Fig. 1. A categorization of sociotechnical digital twins

These six SDT categories can, of course, be combined, but the perspective that matters in this paper is the tangible implementation of their integration.

4. Tangibility of sociotechnical digital twins

An SDT is a virtual object or agent. It appears to be a vivid image of a real-world entity, its twin. Its tangibility is the distance to this real-world twin that one can grasp both physically and figuratively (i.e., mentally or cognitively).

Tangibility can be investigated and assessed based on five key attributes: complexity, flexibility, maturity, stability, and sustainability [7]. They can be quantitative or qualitative:

- Some sociotechnical systems' digital twins are too complex to grasp easily. Complexity arises from the number of parts and their interactions. When this number is large, complexity is high. There are ways to reduce complexity, including separating certain parts from the rest of the system and studying them in isolation. However, we need to be careful when separating a part, verifying that its interconnectivity with the rest of the system is minimal, if not nonexistent. In the human body, hands are separable, can be studied in isolation, and put back together. Otherwise, this part must be analyzed in conjunction with the rest of the system (e.g., as is the case with the human brain). When developing a discount SDT, it is crucial to consider separability seriously.
- SDT flexibility can be viewed from several perspectives throughout the life cycle of a sociotechnical system. The first flexibility issue is about the ease of modification. The second concerns usability and usefulness across a wide variety of situations. The third concerns repair, adaptation to evolving cultures, and eventually dismantling. Summarizing, an STS is considered flexible when it is easily adaptable, allowing stakeholders to operate within it or work with it with little difficulty. The more these flexibilities are present, the more tangible the corresponding STS becomes, both physically and figuratively.

- SDT maturity ensures the STS corresponding to it is mature. Three types of maturity need to be coordinated: technological, human, and organizational. The assessment of technological maturity is already covered by TRLs (Technology Readiness Levels) [8] [9]. However, TRLs do not cover the entire spectrum of STS maturity and SDT maturity repercussions. The practice's maturity also needs to be covered. This is why HRLs (Human Readiness Levels) were developed [10]. Ultimately, when a society is not culturally prepared to accept a new concept, it becomes challenging to sell it. This is why maturity must be investigated at the organizational or societal level. ORLs (Organizational Readiness Levels) have recently been proposed to address this aspect [11]. Obviously, TRLs, HRLs, and ORLs need to be coordinated. The more these three types of maturity are covered, the more tangible the corresponding STS becomes.
- The stability of an STS requires that its SDT be stable in nominal and off-nominal situations. In the former case, stability can be passive (i.e., an STS returns to a stable state when disturbed) or active (i.e., an STS requires appropriate action to maintain stability when [constantly] disturbed). In the latter, stability leads to resilience.
- Sustainability relates to projection into possible futures. SDT sustainability is tangible when the corresponding SDT can be modified in the long term. Sustainability and stability are obviously related concepts…

Assessing these attributes requires appropriate test methods. Aircraft are incrementally validated through flight tests; similarly, digital twins must be validated through operational tests in HITLSs (i.e., conducted in a digital environment with real human operators). Indeed, HITLSs are crucial for testing SDTs using the five tangibility attributes.

5. The role of digital twins in human-AI teaming

The incorporation of software into machines, and more specifically, artificial intelligence (AI), is transforming sociotechnical systems into socio-cognitive systems, necessitating new models and metrics for joint human-machine systems. We have already proposed and implemented a knowledge representation that combines human and machine intelligence [12]. This system can be viewed as a representation of either an artificial or a natural entity, which helps implement a sociotechnical digital twin (Figure 2).

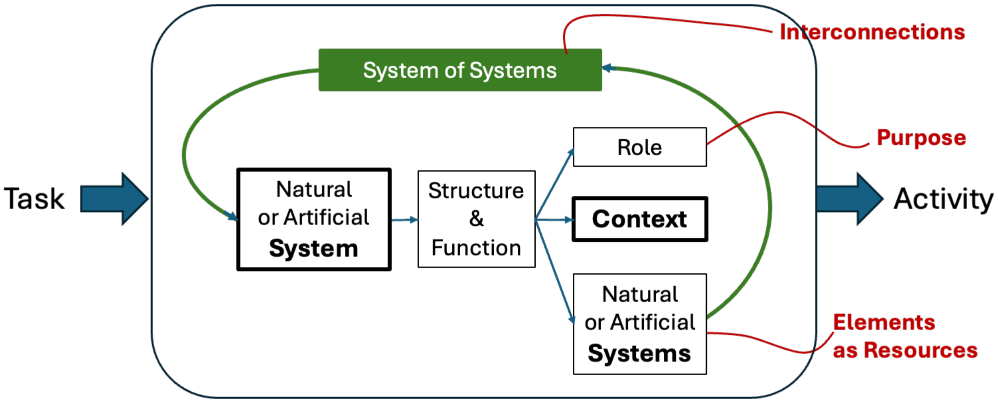

Fig. 2. A simple ontology for the implementation of a sociotechnical digital twin.

Each system has at least a structure and a function, which have roles, validity contexts, and resources that are themselves systems. This definition is intrinsically consistent with the definition of a system of systems. Roles are expressions of purpose, and systems are elements of a larger system of systems interconnected through relationships. Additionally, a system can be physical or figurative (i.e., conceptual or cognitive). A system, as a representation in the systems science world, can be considered an agent in the AI world. This agentic representation believes that a system/agent transforms a task (i.e., what is prescribed) into an activity (i.e., what is effectively performed). This representation is used in the systemic cognition theory [13].

The representation shown in Figure 2 is recursive and chainable, an excellent asset for testing the tangibility of a sociotechnical system. First, complexity can be tested by counting the number of links between systems once the proper levels of granularity are determined. Second, flexibility is also a property of this representation, in the sense that it allows for the modifiability of roles, contexts, and resources associated with functions and structures, as well as the creation or removal of existing systems. Third, maturity can be expressed through the stabilization of emergent systems discovered in HITLSs (i.e., the more emergent systems are learned and mastered, the more the sociotechnical system at stake becomes mature across technical, organizational, and human perspectives). Fourth, stability can be tested using various HITLSs based on different scenarios and activity analyses, which are formalized by the systemic cognition representation presented in Figure 2. These task and activity analysis formalizations are similar to BPMN graphical diagrams [14]. Fifth, sustainability projections can be analyzed by assessing the consistency of the systemic cognition representation diagrams.

When human-AI teaming is at stake, in addition to these five attributes of tangibility, the tangibility of AI systems themselves needs to be tested [15]. AI systems may have various facets, including skill-based behavior capabilities (e.g., image recognition, speech generation and recognition, machine learning, deep learning, and generative algorithms), rule-based behavior capabilities (e.g., case-based reasoning, rule-based systems, and supervised learning), and knowledge-based behavior capabilities (e.g., machine as a partner with data science capabilities). In all cases, issues such as trust, collaboration, operational performance, explainability, completeness of data-driven algorithms, consistency of case-based systems, and context-sensitive usefulness of more profound knowledge are considered. More generally, the issue of context in AI remains unresolved, and even if human experts in a field can commit errors, they are susceptible to context. The systemic cognition representation provided in Figure 2 enables the generation of both procedural and declarative diagrams for analyzing these issues. This is what PRODEC supports.

6. The role of sociotechnical digital twins in PRODEC

PRODEC is a scenario-based design method created to support human systems integration of sociotechnical systems by developing procedural scenarios, using them in HITLSs, analyzing the activities they produce, and reintegrating emerging functions and structures into the STS under development. It is currently tested and incrementally improved on real-world industrial projects. PRODEC is a semi-formal method grounded in both systems engineering and human-centered design, with a focus on human systems integration. Indeed, PRODEC was created to exploit the distinction between tasks and activities, between what is prescribed to be done and what is effectively done; this is Axis 1 of the method. PRODEC also initiates the analysis of what currently exists, denoted “As-Is”, and projects toward possible futures using a target STS model, denoted “To-Be”; this is Axis 2 of the method. There is another direction that makes PRODEC unique: Axis 3, which is based on the procedural-declarative distinction and distinguishes between the ‘how’ and the ‘what’. Another direction concerns emerging behaviors and phenomena resulting from HITLS across various scenarios, as validated by domain experts; this is Axis 4. Finally, Axis 5 is the ultimate analytical process that transforms raw data into functional and structural information, which helps improve the design of the STS.

Instead of waiting for the completion of the overall system (e.g., an aircraft), PRODEC considers the space for control and management of the system being designed (i.e., commonly referred to as the user interface) to be a subsystem of the overall system of systems. The overall system can be designed and developed in a virtual world, which we refer to as the virtual sociotechnical digital twin within a virtual human-centered design process (Figure 3). Then, certain aspects of the overall system are incrementally made tangible to create a hybrid sociotechnical digital twin that involves technology, organizations, and people, with some systems remaining virtual for further refinement (i.e., maintaining design flexibility at the highest possible level). After several iterations, the overall sociotechnical system becomes more mature (i.e., essential functions and structures have emerged for activity analysis, and the system has become more tangible, both physically and figuratively).

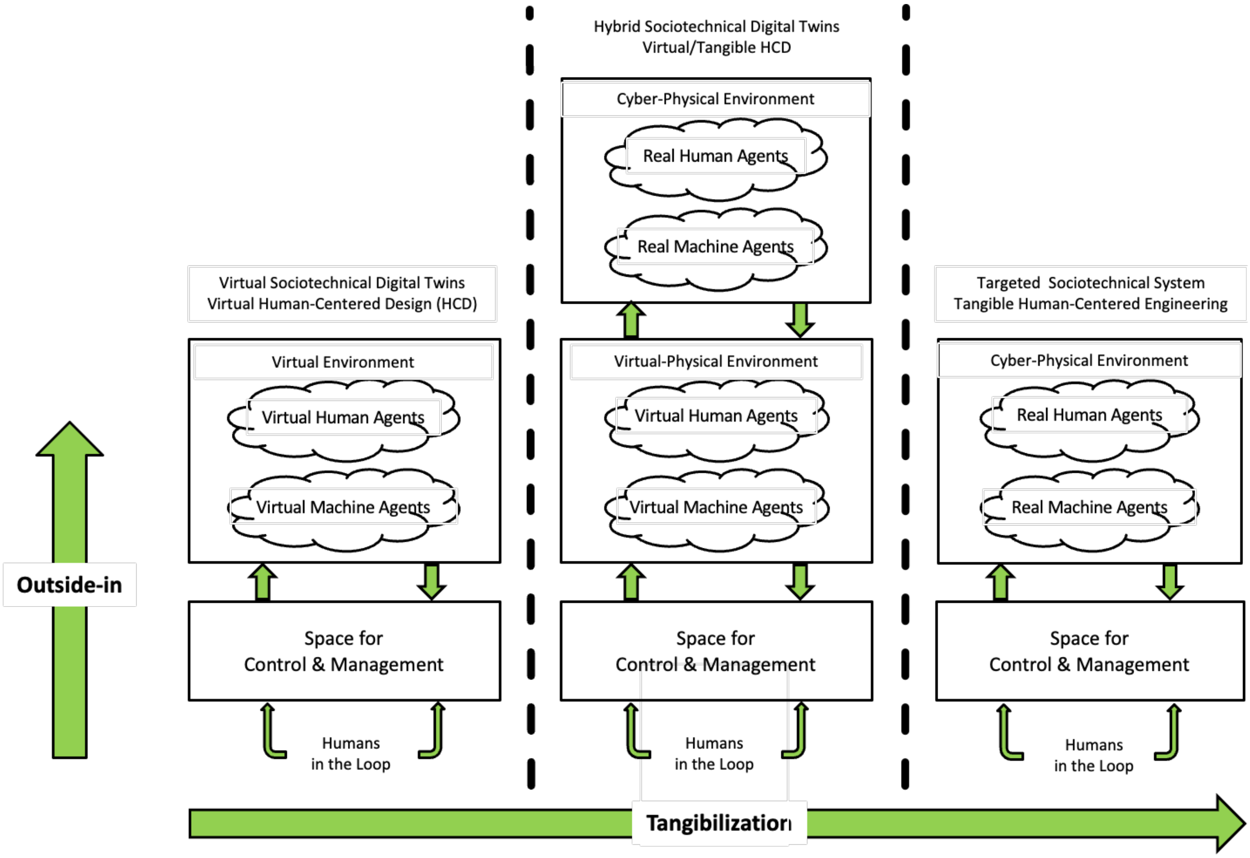

Fig. 3. Design and development life cycle of a sociotechnical system from virtual to tangible.

This approach is called “outside-in” to express the process “from purpose to means” (i.e., from people’s requirements to technology, organizations, and competencies development, in contrast with the traditional engineering practice that goes “inside-out”, from means to purpose (i.e., from technology to the adaptation of people and organizations).

This approach was employed in the MOHICAN project, which focused on designing a future air combat system, specifically a virtual assistant onboard a fighter aircraft [16]. This VA is firmly based on AI algorithms. Its integration within the overall sociotechnical system has been tested in HITLS using three metrics: trust, collaboration, and operational performance. MOHICAN results have already been published [16] [17]. MOHICAN was the first research project that contributed to the development of the PRODEC process (Figure 4), which has been incrementally improved and utilized in numerous other projects, such as a virtual remote air traffic tower, a telerobotics system for offshore oil and gas drilling platforms, the automation of railways [18], and remote maintenance of helicopter engines [19].

8. Conclusion and Perspectives

Sociotechnical digital twins (SDTs) help develop human systems integration in sociotechnical systems. This concept has been proven to be a significant asset in digital engineering, particularly in considering people and organizations seriously in the design and development processes. An ontology has been developed, leading to the systemic cognition theory that supports the development of SDTs. This ontology provides a functional language for implementing HTILSs and further activity analysis based on tangibility metrics, which are indispensable tools for identifying emerging functions and structures of the STS being developed. A PRODEC software platform is currently under development [2] [17].

Human systems integration (HSI) has a long way to go [13] [20]. SDTs are crucial tools for the corresponding development. Sociotechnical systems [1] are currently being analyzed, structured, and functionalized, ultimately leading to a better understanding, particularly as they become increasingly digitalized. The notion of context is fundamentally an issue that warrants further investigation [21].

The initial ontology developed for the topic requires further development to cover the broad scope of HSI. It is by carrying out industrial and, more generally, real-world projects that this kind of ontology will make sense. It will also become sustainable by implementing and testing it in the real world.

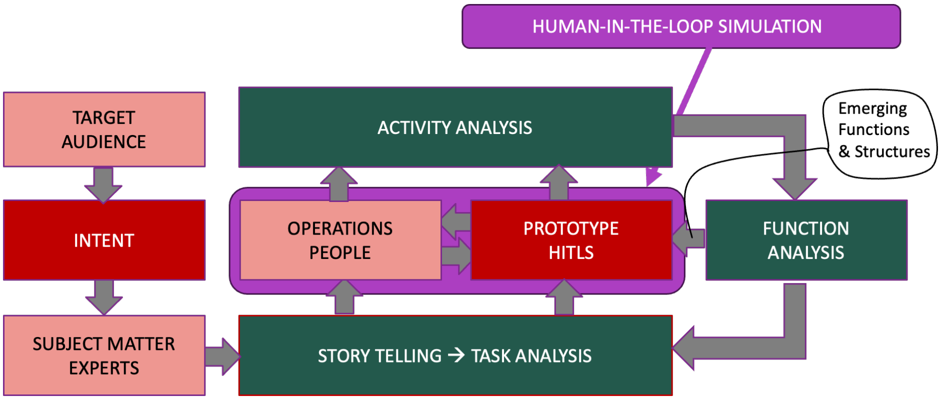

Fig. 4. PRODEC as a scenario-based design method.

Integrating the human element into the design and management of sociotechnical digital twins opens research directions for operationalizing tangibility metrics, developing validation methods, and extending the framework to emerging application domains. While the framework needs further refinement and empirical validation, it has been successfully used in several projects [2, 4, 16, 18, 19, 21]. Hoping that this paper will generate valuable discussion among systems engineering researchers and practitioners.

Acknowledgements

This work could not have been achieved without the invaluable support of the FlexTech chair's industrial partners. At the same time, I was a University Professor at CentraleSupélec (Paris-Saclay University) and the ESTIA Institute of Technology, and Chair of the INCOSE HSI Working Group. I would also like to thank all my students and colleagues who helped make this work a promising field. Finally, thank you to the CSER-2026 reviewers for their comments and suggestions.

References

1. Boy GA (Ed.) *Handbook of Sociotechnical Systems: A Human Systems Integration Approach*. Boca Raton, FL: CRC Press; 2026. ISBN-13: 978–1041122289; 2026.
2. Boy GA, Masson D, Durnerin E, Morel C. PRODEC for Human Systems Integration of Increasingly Autonomous Systems. *Systems Engineering Journal*. Wiley, USA; 2024. DOI:10.1002/sys.21751. https://authorservices.wiley.com/api/pdf/fullArticle/17929898.
3. Boy GA. *Design for Flexibility - A Human Systems Integration Approach*. Springer Nature, Switzerland; 2021. ISBN: 978-3-030-76391-6.
4. Camara Dit Pinto S, Villeneuve E, Masson D, Boy GA, Urfels L. Reality anchor methodology: how to design a digital twin to support situation awareness, Journal of Engineering Design; 2024; DOI: 10.1080/09544828.2024.2336838.
5. Boy GA. Model-Based Human Systems Integration. In the *Handbook of Model-Based Systems Engineering*, A.M. Madni & N. Augustine (Eds.). Springer, USA; 2022. DOI: https://doi.org/10.1007/978-3-030-27486-3_28-1.
6. Boy GA. *Human Systems Integration: From Virtual to Tangible*. CRC Press – Taylor & Francis Group, USA; 2020. https://www.taylorfrancis.com/books/9780429351686.
7. Boy GA. *Tangible Interactive Systems: Grasping the Real World with Computers*. Human-Computer Interaction Series. Cham: Springer International Publishing; 2016. DOI: 10.1007/978-3-319-30270-6.
8. Banke J. *Technology Readiness Levels Demystified*. NASA Technical Document; 2010.

9. Heder M. From NASA to EU: the evolution of the TRL scale in Public Sector Innovation. *The Innovation Journal*. 22, pp. 1–23; 2017.
10. See J. Human Readiness Levels Explained. *Ergonomics in Design The Quarterly of Human Factors Applications*, 29(4); 2021; DOI: 10.1177/10648046211017410.
11. Boy GA. Socioergonomics: A few clarifications on the Technology-Organizations-People Triad. *Proceedings of INCOSE HSI2021 International Conference*, Wiley Online Lib..; 2021.
12. Boy GA. An Epistemological Approach to Human Systems Integration. *Technology in Society Journal*, 102298; 2023; https://doi.org/10.1016/j.techsoc.2023.102298.
13. Boy GA. Systemic cognition: A few epistemological clarifications. ESTIA Scientific Report, 2015, and a Journal article to appear in 2026.
14. Object Management Group. *Business Process Model and Notation* (BPMN), Version 2.0; 2013.
15. Boy GA. Is the machine a partner or a Tool? A significant issue of Human-AI Teaming. *AI4SE & SE4AI Workshop 2023*. George Washington University, Washington, D.C., USA; 2023.
16. Boy GA, Morel C. The Machine as a Partner: Human-Machine Teaming Design using the PRODEC Method. *WORK: A Journal of Prevention, Assessment & Rehabilitation*. Vol. 73, no. S1, pp S15-S30; 2022. DOI: 10.3233/WOR-220268. IOS Press Content Library.
17. Boy GA. PRODEC: A Method and Platform. For Human Systems Integration of Human-AI Teams. *AI4SE & SE4AI Workshop 2024*. George Mason University, Arlington Campus, Arlington, VA, USA; 2024.
18. Sun Y, Boy GA, Sango M, Barros A. PRODEC-Based Task Analysis for the Design of Semi-Automated Trains. *Complex System Design and Management* Conference, Beijing, China. pp.220-230; 2023, 10.1007/978-981-99-6511-3_20. hal-04313336.
19. Lorente Q, Villeneuve E, Merlo C, Boy GA, Thermy F. Sociotechnical System Digital Twin as an Organizational enhancer applied to Helicopter Engines Maintenance. *IEEE International Conference on Industrial Engineering and Engineering Management (IEEM),* Kuala Lumpur, Malaysia; 2022. 10.1109/IEEM55944.2022.9989843. hal-03920816.
20. Boy GA, & Kennedy G. (Eds.). *Human Systems Integration Primer Volume One*. San Diego, CA, USA: INCOSE; 2023; ISBN 978-1-937076-12-2.
21. Disdier A, Masson D, Jankovic M, Boy GA. Defining and Characterizing the Operational Context for Human Systems Integration. *Systems Engineering Journal*. Wiley, USA; 2024.