A Context Acquisition Methodology for the Design of Complex Sociotechnical Systems

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Abstract. Complex sociotechnical systems are likely to display emergent properties that are difficult to anticipate at design time. One of the causes for emergence is the system's sensitivity to its own operational context. Since context heavily drives the behavior of such systems, a proper HSI endeavor should define the relevant contextual elements during the early stages of the lifecycle, even before the system has been integrated and project resources have been committed. This paper presents an early-stage context elicitation methodology along with a companion software tool in development combining the HSI literature, the context literature and scenario-based design principles. The use of our tool is illustrated through the case study of the design of a remote air traffic control center.

Introduction

Human Systems Integration (HSI) seeks to consider the human and organizational aspects during the design, development, manufacturing, operation and retirement of a system. This is a particularly important endeavor for complex sociotechnical systems that elicit emergent behavior and properties (Boy, 2022) which are difficult to predict at design time. Emergence stems from the interaction between the elements of the whole system, which cannot be reduced to these elements individually (Checkland, 1999). The INCOSE Complexity Primer (INCOSE, 2016) adds that one candidate approach to address system complexity is to "*maximize description of emergent properties in scenarios and mission definition*". It also states that "*emergence will not be observed until the system is considered as a whole*".

Air traffic control (ATC) towers and remote centers are examples of complex sociotechnical systems. ATC towers involve machine and human agents and are part of a more extensive ATC system of systems (SoS), two objectives of which are to prevent collisions and maintain an orderly flow of air traffic, according to the *International Civil Aviation Organization (ICAO)*. The feasibility and operationnability of ATC remote centers have been studied as an alternative to ATC towers (Fürstenau, 2014). Such centers would supervise the air traffic from a distant airfield. Their development is motivated by the reduction in tower construction and maintenance costs, and by the pooling of resources from several low-traffic airfields which would be supervised by a single remote center.

Both towers and remote centers are complex because their behavior heavily depends on the *operational context* in which they are immersed. Context has a strong influence on the resources available to these system's agents and, therefore, determines the activity that these agents will actually perform, which may differ from the tasks prescribed during the design stage (Boy, 2021). In this paper, we present a scenario-based design (SBD) methodology along with a companion software tool still under development that helps capitalize on context knowledge during the elicitation of scenarios in collaboration with subject matter experts (SME). We discuss the properties of the operational context which our methodology is built around, and we illustrate the future use of our tool through the case study of the design of a remote ATC center. Section 2 will provide a short review of context definitions and properties. Section 3 will relate context to the HSI literature and derive an SBD-based contextualization methodology for the design of complex sociotechnical systems. Section 4 will illustrate the proposed methodology through the case study of ATC operations. Section 5 will conclude and set the agenda for future work.

Related work on context

Context research spans multiple engineering and non-engineering domains, from linguistics and philosophy to artificial intelligence (McCarthy, 1993) and cyber-physical systems (Brings, 2018; Daun, 2022). Therefore, there cannot be one consensual definition of context. Paradigms have been developed to understand the notion of context with respect to human behavior (Brezillon, 2005) and mission activity (Gonzalez, 2017). These works emphasize that context is a partial representation of knowledge of the world, which includes only the elements that influence the execution of tasks performed by agents of the system at a given time.

The notion of context has yet to be developed when it comes to Systems Engineering (SE) and HSI. The NASA HSI Handbook (NASA, 2021) mentions the operational or mission context of systems, but does not define it explicitly. The INCOSE SE Handbook (INCOSE, 2015) and SEBoK (SEBoK, 2021) relate context to the environment that resides outside the system of interest. These discussions of context do not highlight the dynamic nature of context, which can no longer be treated only as a static representation of what surrounds the system. Instead, there is a need to build a generalized model for context tailored to the scope of HSI.

A previous study of ours (Disdier, 2024) already provided a thorough exploration of the above-mentioned context literature and constructed from it the following definition of the operational context of complex sociotechnical systems: "*context is* a *historical sequence of situations that influence and help explain the behavior of a focus"* (Figure 1). We also established in the same paper six inherent properties of context, namely: context is specific (context is always relative to some focus, which is defined as a couple (system, function)), curated (only a few contextual elements have a real relevance to the system and its behavior), holistic (the whole system's context is more than the individual contexts of its subcomponents), transient (context is not static and definitive but changes through time), entangled (context affects the availability of the system's resources, and system behavior affects context), and persistent (a contextual element's former value can still have a relevance to the current situation). We will build further upon these definition and properties in the next section and relate them to HSI. Our objective is to propose a methodology that enables the acquisition of context information during the early design of complex sociotechnical systems.

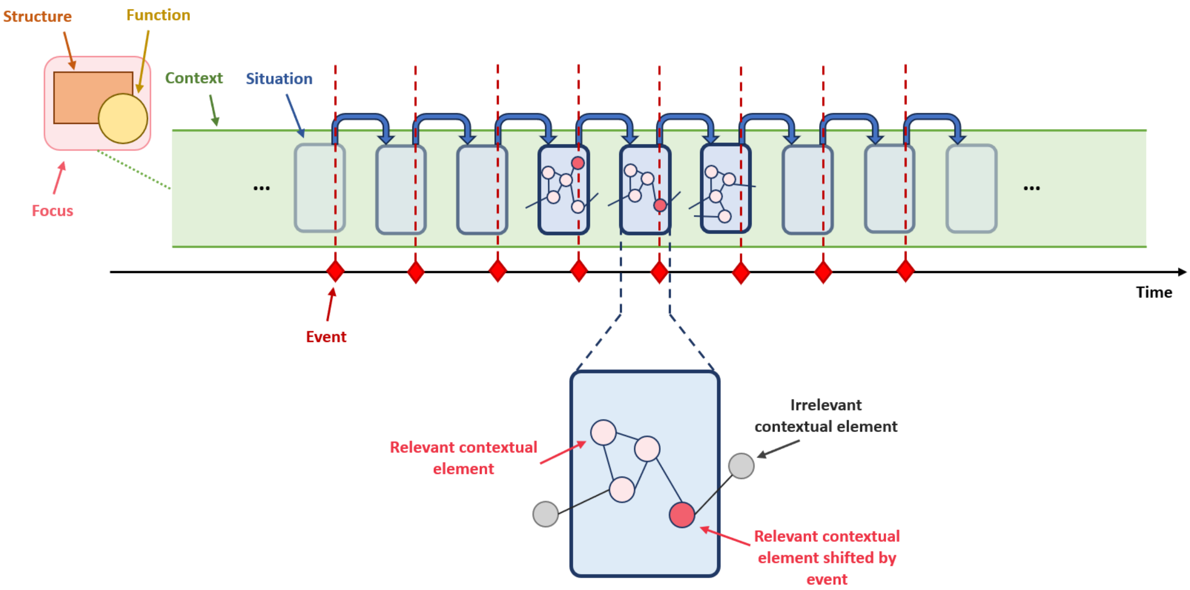

Figure 1. Our definition of the operational context

An HSI-based scenario contextualization methodology

The HSI literature recursively defines a system as made of a structure and a set of functions, each function being characterized by a role and enabling resources, which are themselves systems (Boy, 2021). What results from this definition is that altering the context directly alters the resources, and altering the resources may have a consequence on the achievability of the underlying functions, thereby breaking the whole resource hierarchy of the system (Figure 2). Therefore, comprehending context evolution and its impact on the system's operations is crucial to understanding overall system behavior.

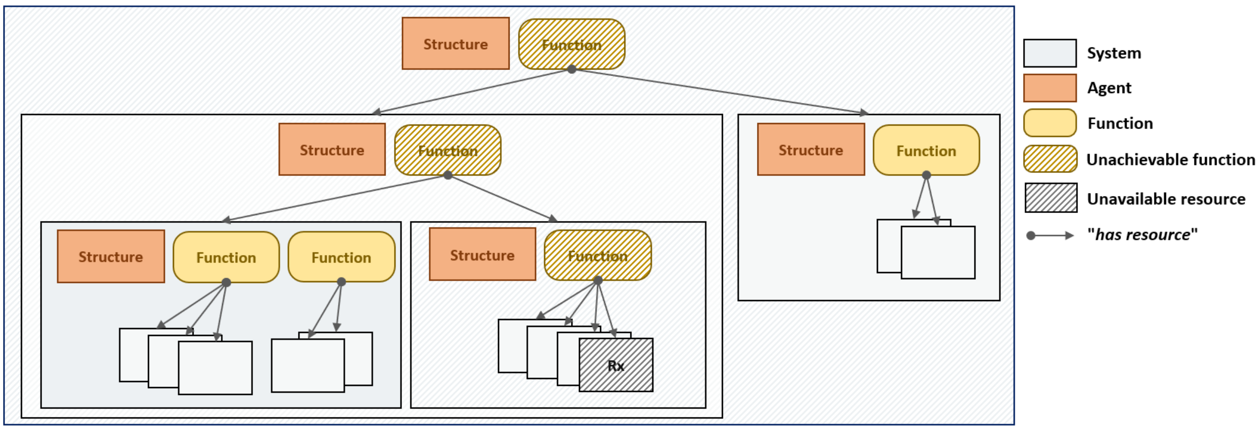

Figure 2. An HSI view of a system of systems comprising multiple resources. When resource Rx is unavailable for some reason, the function of which it is a resource can no longer be achieved, and this unachievable function itself impedes the feasibility of higher-level functions depending on it.

Our definition implies that context is a long-term entity defined by a sequence of situations. A situation captures all the information that is relevant to understanding the behavior of a system at a given time. This information can be broken down into smaller pieces called *contextual elements*. A contextual element has a value that can change through time. The resources of a system's function are sensitive to the values of the contextual elements that compose the current situation. Consequently, altering a contextual element's value can impact the availability of a system's resource. When a resource is no longer available, the system must adapt its activity to cope.

SBD approaches (Rosson, 2002) emphasize the importance of understanding the *use* of a system expressed in the forms of scenarios. A more complete picture of how the system will be used and behave should also include knowledge of the relevant contextual elements that may influence the conduct of the scenarios. Furthermore, the scenarios describe procedural knowledge (i.e. what the system and its constituents do), which then needs to be backed up with declarative knowledge (i.e. what the system has to be made of to support the execution of the scenario). Therefore, when system designers collaborate with SMEs during the early stages of the system life cycle, they should capture scenarios describing the use of the system, along with the set of resources (i.e. subsystems made of structures and functions) needed to carry out these scenarios, as well as the nature of the contextual elements that may influence how these scenarios are carried out.

When the system of interest of the aforementioned process already exists, the set of elicited scenarios and resources are said to be AS-IS. Trying to adapt such systems to new environments and procedures involves modifying the context to see how this change reflects in both procedural and declarative knowledge (Boy, 2023) of the system (e.g. we want to start from a traditional physical ATC tower and progressively get towards a remote ATC center by turning the tower context into a remote context, see Figure 3). We do so by changing the values of contextual elements, which will have an impact on the availability of the resources and, indirectly, on the scenarios. Designers should collaborate further with SMEs to discuss how to adapt the AS-IS scenarios and AS-IS resource sets and iteratively turn them into TO-BE scenarios and TO-BE resource sets.

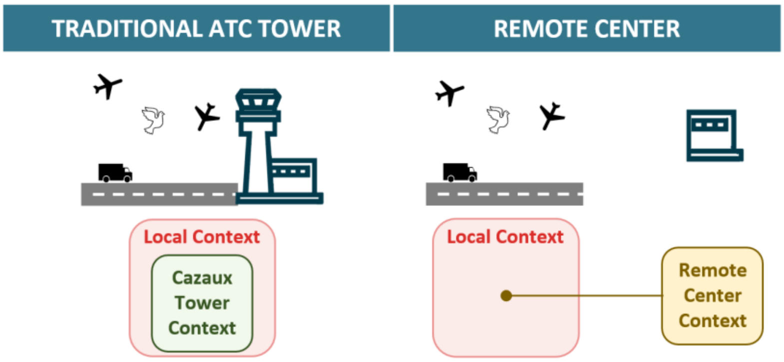

Figure 3. When we turn from an ATC tower to a remote center, we get from a local context to a different remote context

The context alteration phase should be followed by a series of human-in-the-loop simulations (HITLS) (Rothrock, 2011). These simulations aim to analyze the activity of human agents when they play the TO-BE scenarios on a virtualized prototype of the system constructed with the help of information contained in the TO-BE resource sets. Indeed, the activity may differ from the prescribed tasks developed in the scenarios (Boy, 2022). As such, the simulations may help refine both scenarios and resource sets and consolidate them with contextual information that was not anticipated during the exchanges between designers and SMEs. Figure 4 gives a high-level overview of the entire methodology.

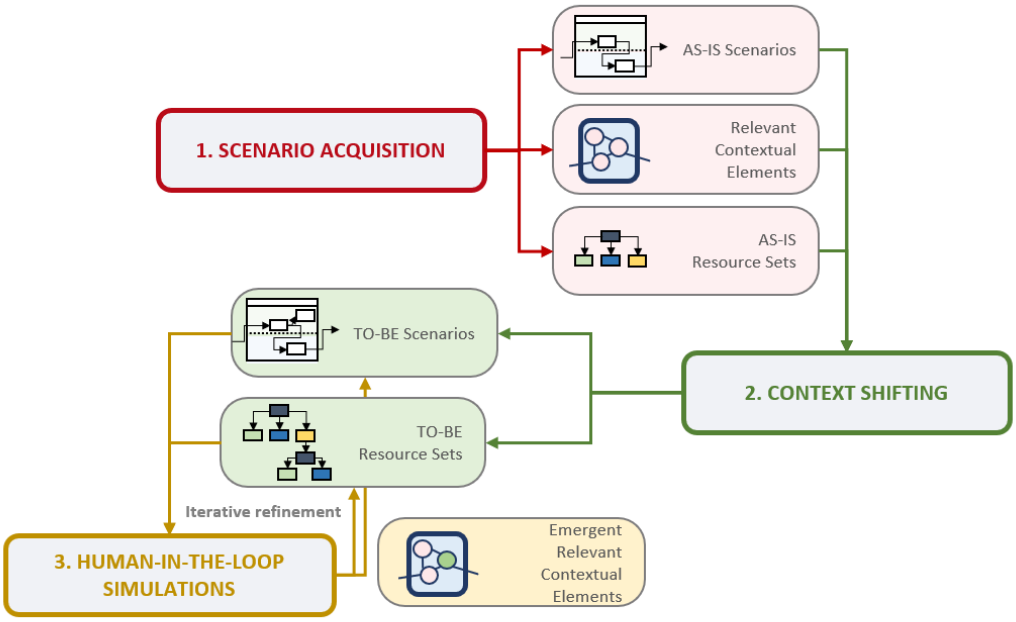

Figure 4. High-level view of the scenario contextualization methodology

Application to ATC operations

In this section, we illustrate the methodology described in Section 2 and study how we would address the contextualization of an ATC tower. We developed a short scenario in collaboration with former ATC controllers (Figure 5).

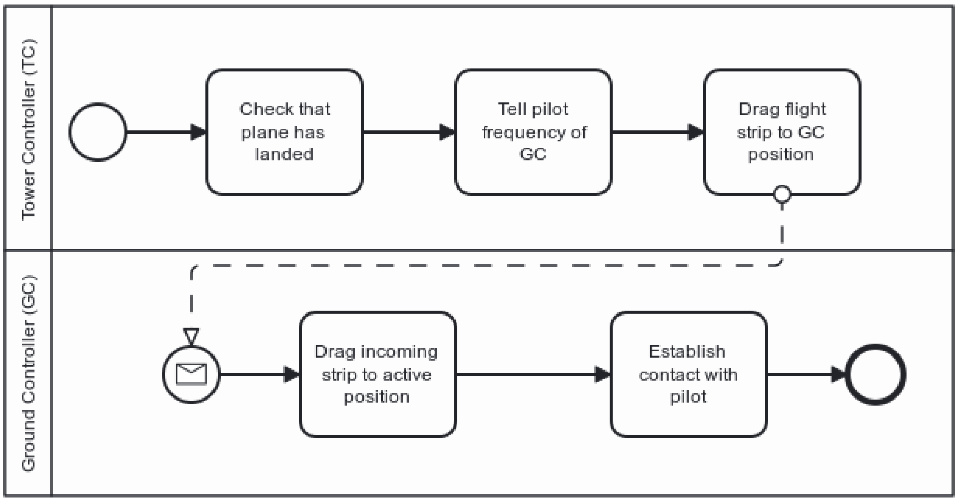

Figure 5. A scenario for the transfer of responsibility from the Tower Controller (TC) to the Ground Controller (GC)

The scenario involves two actors: the Tower Controller (TC) and the Ground Controller (GC). One function of the TC is to supervise the landing of any plane on the track. Once the plane has successfully landed, the TC transfers their responsibility for the plane's safety to the GC, who will guide the arriving pilot from the track to the apron. The transfer process is carried out through an HMI by drag-and-dropping the corresponding numerical flight strip (i.e. the screen area containing all necessary information about the flight) towards the right of the screen.

This scenario is currently implemented in traditional ATC tower environments. If we projected to design a remote ATC center, we would want to adapt this scenario from a local to a remote context (as discussed and illustrated in Figure 3). Therefore, we must elicit the resources needed to achieve this scenario through semi-structured interviews with SMEs. The SMEs we worked with helped us construct the underlying AS-IS resource tree of Figure 6. This resource set tells us that the scenario of Figure 5 implements one of the functions of the tower cab, namely "Ensure that controllers can transfer flight responsibility to each other". The cab system comprises the GC and TC subsystems, each being assigned enabling functions to establish contact with the pilot and perform the actual transfer through their respective workstations. The further down we go in the tree, the more granular the functions. The leaves eventually become essential physical and cognitive functions (e.g. "see", "tell" and "transform signals").

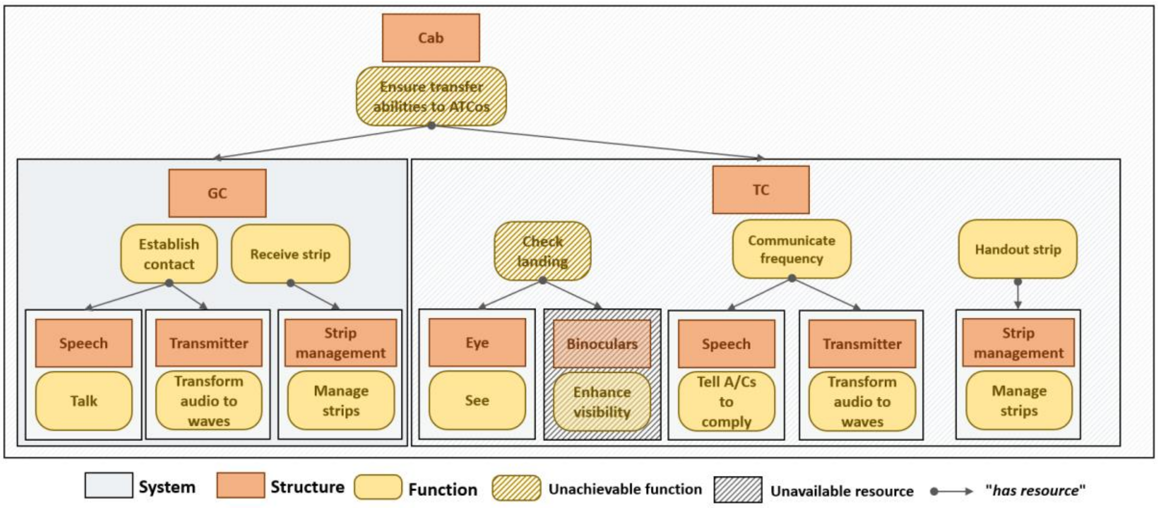

Figure 6. The underlying AS-IS system's resource hierarchy in support of Figure 5's transfer scenario

Each resource is sensitive to a subset of contextual element values. For instance, the "Binoculars" resource, which the TC may use to assert that the plane has landed, becomes ineffective when the contextual element "Weather" is turned to "Heavy Fog". Consequently, the function that this resource supports (i.e. "Check Landing") can no longer be carried out successfully, and we must elect a new set of supporting resources for this function which do not depend on the "Weather" contextual elements. Designing a new remote center then amounts to simulating how changes in relevant contextual element values (i.e. how transitioning from one situation to another) affect the activity of the system and its subcomponents. Furthermore, one of the six properties of contexts we formulated in the Related Work section states that a contextual element's former value can still be relevant to the current situation. For instance, a rainy weather an hour ago will affect the landing and departure procedures for as long as the track is wet. This means that a resource can be sensitive to the sequence of values taken by a contextual element through time and not only to the current value of this contextual element.

Conclusion and future work

The behavior of complex sociotechnical systems is strongly related to the operational context of these systems. In this paper, we articulated the principles of HSI with the characteristics of context and established a methodology for eliciting contextual information during the design stage of systems. Our methodology relies on close collaboration with SMEs to construct scenarios and information about the resources needed to achieve them. The methodology aims to identify the relevant contextual elements that influence the system as early as possible. More precisely, the relevant contextual elements are the variables that influence the availability of the resources, therefore impacting the achievability of the underlying scenarios. When we design a system of interest, we create new contexts for the human and machine agents that compose the system. Understanding how the system and its context relate to each other is crucial to making adequate decisions about the design of this system.

We illustrated the application of our methodology to the case study of the design of a remote ATC center based on the feedback of controllers with experience in traditional towers. Our next step in this research project is to carry out an entire contextualization of a real-life use case of ATC operations, from the elicitation of AS-IS scenarios and resource sets to the architecture of a TO-BE prototype whose resources have been derived from the contextualization stage, which is at the core of our methodology. To this end, we started to develop a software tool to assist the HSI practitioner in capitalizing on the information collected from the involved SMEs. Figure 7 shows a screenshot of our tool in its current version.

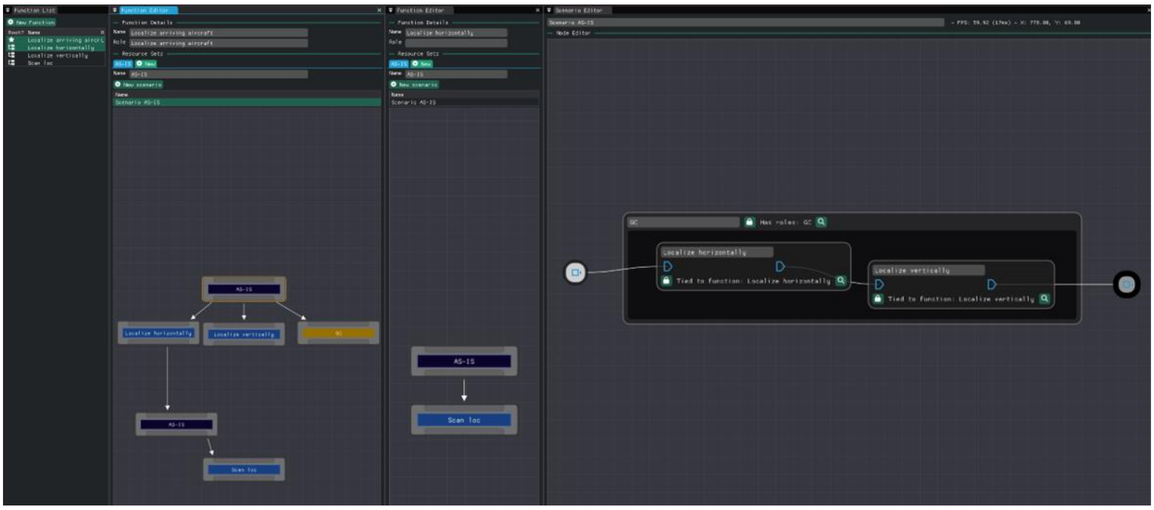

Figure 7. Screenshot of the tool during the scenario acquisition stage

The right-hand side is a canvas for constructing scenarios in a BPMN (Business Process Model)-like formalism. The resource tree is automatically constructed on the left-hand side as the practitioner adds nodes to the scenario. Each resource can then be tied to particular contextual element values. The eventual purpose of this tool is that changing context by creating new situations with different contextual element values will highlight which resources and which scenarios must be adapted to these newly crafted situations.

References

Checkland, P. 1999. *Systems Thinking, Systems Practice.* New York, NY, USA: John Wiley & Sons.

INCOSE. 2016. *A Complexity Primer for Systems Engineers*. TP-2016-001-01.0.

Fürstenau, Norbert. (2014). Virtual and Remote Control Tower - Research, Design, Development and Validation. 10.1007/978-3-319-28719-5.

Boy, G.A. (2021). Human Systems Integration and Design, Chapter 2 of the Handbook of Human Factors and Ergonomics, Gavriel Salvendy & W. Karwowski (Eds.), 5th edition, Wiley, USA.

John McCarthy. 1993. Notes on formalizing context. In Proceedings of the 13th international joint conference on Artifical intelligence - Volume 1 (IJCAI'93). Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 555–560.

Brings, J., Daun, M., Hildebrandt, C., & Törsleff, S. (2018). An Ontological Context Modeling Framework for Coping with the Dynamic Contexts of Cyber-physical Systems. International Conference on Model-Driven Engineering and Software Development.

Daun M, Tenbergen B. Context modeling for cyber-physical systems. *J Softw Evol Proc*. 2023; 35(7):e2451. doi:10.1002/smr.2451

Brézillon, P. (2005). Task-Realization Models in Contextual Graphs. In: Dey, A., Kokinov, B., Leake, D., Turner, R. (eds) Modeling and Using Context. CONTEXT 2005. Lecture Notes in Computer Science(), vol 3554. Springer, Berlin, Heidelberg. https://doi.org/10.1007/11508373_5

Gonzalez, Avelino. (2017). Modeling Human Actions through Context. Modélisation et utilisation du contexte. 17. 10.21494/ISTE.OP.2017.0147.

Rippy, L. O. (2021). *NASA Human Systems Integration Handbook* (No. NASA/SP-20210010952).

INCOSE (2015) Systems Engineering Handbook: A Guide for Systems Life Cycle Processes and Activities. 4th Edition, John Wiley & Sons, I., Hoboken.

SEBoK Editorial Board. 2023. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 2.9, N. Hutchison (Editor in Chief). Hoboken, NJ: The Trustees of the Stevens Institute of Technology.

Disdier A, Masson D, Jankovic M, Boy G-A. (2024). Defining and characterizing the operational context for human systems integration. Systems Engineering. 2024; 1-13. https://doi.org/10.1002/sys.21775

Rosson, Mary Beth & Carroll, John. (2002). Scenario-Based Design. The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications. 1032-1050. 10.1201/b11963-56.

Boy, G.A., Masson, D., Durnerin, E. & Morel, C. (to appear). PRODEC for Human Systems Integration of Increasinlgy Autonomous Systems. Under review.

Rothrock, Ling and Narayanan, S. 2011. Human-in-the-Loop Simulations: Methods and Practice. Springer Publishing Company, Incorporated.

Boy, G.A. & Morel, C. (2022). 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. DOI: 10.3233/WOR-220268.