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An epistemological approach to human systems integration

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ABSTRACT

Can we contribute to developing a consistent terminology and, to some extent, an acceptable ontology in the rapidly expanding field of human systems integration (HSI)? We often define HSI as a process and a product at the confluence of several areas, such as systems engineering, human factors and ergonomics, information technology, and specific sectors, such as aerospace, health, and energy. It is a broader transdisciplinary field in our increasingly complex human-machine world that focuses on integrating technology, organizations, and people within a complex sociotechnical system throughout its life cycle. Therefore, HSI is no longer a question of usability and user interface design once a complex machine is technologically developed, but also about considering people and organizations early on in the design and development processes. Indeed, rooted in industrial engineering research and operational worlds, HSI requires a deeper foundation based on an epistemological approach. This assertion is even more crucial today as technology has become predominantly digital, and, more specifically, the concept of the digital twin is emphasized because it has become essential to support model-based HSI. In other words, software-based assistant systems are replacing traditional tools. Therefore, appropriate social-cognitive (multi-agent) models and methods are helpful throughout the life cycle of contemporary sociotechnical designs to account for the complexity and tangibility of their human-centered context-sensitive architectures, combining procedural and declarative knowledge. By considering these reasons, this article provides a set of fundamental axioms, some theoretical abstractions, and valuable practical models, which are presented and illustrated through the lens of an evolutionary HSI ontology.

1. Introduction

This article is part of a long-term research program that develops epistemological[1] foundations for *Human Systems Integration* (HSI) to support the modeling, design, development, evaluation, and operations of *Sociotechnical Systems*[2] (STSs). HSI has been developing over the last twenty years in defense and space sectors to define people's jobs in large life-critical STSs. It has become an essential topic in the development of Industry 4.0 and its projection into Society 5.0 where people's roles and responsibilities must be at the center of sociotechnical organizations [1–4]. This article hopes to contribute to the development of a consistent terminology and, to some extent, an acceptable ontology for the rapidly expanding field of HSI. Indeed, even though there are various types of contributions in the field, a theoretical foundation of HSI is needed. We use our experience in cognitive engineering, human-computer interaction (HCI), artificial intelligence (AI), human-centered design (HCD), and systems engineering (SE) to support this epistemological approach to HSI.

Our goal here is to structure our discourse on STSs based on our current HSI projects and the extensive work done by others in this area. This is because current conceptions originate from various backgrounds, which can often be misleading due to the resulting languages' lexicon, syntax, semantics, and pragmatics that are not consistent or appropriate enough considering the evolution of HSI [5]. The main research question is then: what are the HSI conceptual models and tools that can support the analysis, design, and evaluation of complex STSs? To answer this question, we need to know more about the triptych *Technology, Organizations, and People* (*TOP model*) [6,7]. Specifically, the notions of system, function, structure, role, social context, and resources, among others, are being investigated within our research program. Based on the Tuomi framework, we expand upon these preliminary investigations to evaluate, integrate, and redesign important organizational models [8]. More

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[1] Epistemology, also called "theory of knowledge," is a subfield of philosophy concerned with knowledge.

[2] In this article, the terms "sociotechnical systems" (STS) and "human-machine systems" (HMS) have the same meaning. The term STS makes the social aspect of HMS explicit, emphasizing socioergonomics [106]. The term HMS clarifies the concepts of human and machine, which is consistent with the concept of human-machine teaming developed for machines including artificial intelligence.

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specifically, the PRODEC modeling and notation approach is currently being developed and applied in two major industrial projects [9,10].

HSI plays a significant role when designing new technologies and/or upgrading existing systems. The conventional HFE approach is primarily based on user interface design and the development of operational procedures in life-critical systems such as can be found in the nuclear industry or the aviation domain, to name a few [11–13]. However, HSI is not just about user interfaces and operational procedures, it is a much deeper endeavor rooted in the science of artifacts,[3] where technology, organizations, and people must be integrated [14,15].

For example, the first typewriters were invented in the early eighteenth century, then commercialized and used in offices during the last quarter of the nineteenth century.[4] Typewriter HSI was a matter of technological opportunity (i.e., the gradual invention of mechanical machines that allowed faster document production). The persistent use of typewriters generated a profound reorganization of office work [16,17] and led to the emergence of new jobs for typists. Typists were resources for others and, sometimes, grouped into typing departments in companies and government offices. These jobs disappeared in the early 1980s when word processing became an accessible capability for everyone. This example shows that technology can be an extension of people's abilities and influence how people organize themselves, emphasizing the essential role of the TOP model.

Another epistemological question is what it means to say HSI is a discipline. For some, it is a part of SE that links people to engineering systems. For others, it is a systemic specialization of HFE. In this article, we want to extend these initial notions of HSI to a broader sense, in which systems represent natural and artificial entities (e.g., people and machines). Moreover, the life of sociotechnical systems is constantly being reorganized according to the evolution (and revolutions) of the artifacts and activities they support. This means that HSI deserves to be better defined and structured through the appropriate language elements that allow us to talk about it accurately. In science, a discipline implies developing and mastering an ontology (i.e., a body of knowledge), which supports the acquisition of appropriate skills and knowledge to become an effective practitioner, and even an expert, in that discipline.

Introducing HSI into the system development process is not new [18,19]. This article can be viewed as a semi-formal, pragmatic account of systems science [20] that proposes an integration ontology (or at least a coherent terminology) that enables us to articulate technology, organizations, and people in a way that is effective in supporting HSI as a discipline. This integration begins with a proper definition of what a system is. HSI expand the systemic HCD perspective toward considering together nature, society, cognition, engineering, technology, and recursively, science [21].

The question remains whether empiricism (e.g., observation of facts) or abstract theory building (e.g., mathematical thinking) should be favored in the sciences, and more specifically in HSI. Let us consider two philosophical approaches [22]: the constructivist one, which considers individual experience and problem-solving to be the keys to sound, but arguably subjective, science, and the realist one, which considers the scientific method, and more specifically, mathematics, results in objective science. A triangle, for example, can be a mental construction of a triangular stone observed on a piece of land or an object that can be mathematically defined very precisely (i.e., three non-colinear lines intersecting at three points).

Constructivists approximate substantial (tangible) observed objects by abstract (mathematical or virtual) constructs: in other words, constructivist models can be considered ontologies characterized by a specific syntax and semantics. **Realists** consider that abstract objects (mathematical or virtual) and their underlying rational mechanisms may have applications in the concrete world: so, realist models can generally be analogs. We can adopt either philosophy but must always be consistent with the corresponding approach. Constructivism starts from observations of the real world and tries to find mental (cognitive) constructs that allow us to give meaning to what is perceived, and realism tries to find examples in the real world a posteriori. However, constructivist and realist approaches sometimes converge. In this article, we propose a progressively refined epistemic model based on knowledge and belief [23], which, at its center, takes into account real-world observations. Given this realist-constructivist distinction, we describe HSI from a historical perspective where the real world is observed through lenses that depend on specific models or theories.

We need to know the motivations and skills of people when we design, develop, and use technologies (i.e., machines or, more generally, artifacts) to facilitate and enhance their activities and, in some cases, to do what they cannot do without artifacts (e.g., fly). However, how people actually use these artifacts is different from what we expect. Therefore, we need to improve upon the explanation of the task-activity distinction. In the proposed HSI approach, "task" refers to what is prescribed [24](pp. 83–111), and "activity" refers to what is effectively performed [25](pp. 193–208). Before the digital engineering era, human operator activity analysis could be performed on existing systems (i.e., before beginning the engineering design of a new system) and after the new system had been developed and, more importantly, integrated. In aeronautics, for example, experimental test pilots participate in the testing of aircraft during flight tests, thereby refining their capabilities and performance, as well as the corresponding operational procedures. What is crucial here is that **technology integration** is still a significant issue in industry. Therefore, add-on solutions, such as user interfaces and operational procedures, have been developed to adapt human operators (i.e., end-users) to the technology-centered machine.

Until the 1980s, most tasks and activities were primarily physical. Thus, human factors have long been linked to biomechanics, physiological health, and safety. For this reason, HFE specialists were primarily physiologists and bio-mechanists. Then, over the last two decades of the 20th century, computing capabilities developed considerably. For example, several onboard computer systems were created and installed on aircraft. More importantly, from this point onward, HCI emerged as a discipline not only because microcomputers invaded all areas of our lives, including our homes, but also because there was a need to master **emerging cognitive activities**. In this way, cognitive psychology and anthropology had a huge role in the development of cognitive engineering [26], which greatly supported HCI. Then, HCI gradually penetrated HFE. HCI researchers and practitioners developed numerous task analysis methods during the 1980s and 1990s, and most importantly, interaction design became an effective practice [27]. HCD began to develop within HCI and thus was limited to computer systems: some have called it Human-Centered Computing! [28].

Then, in the first two decades of the 21st century, the power of software and computer networks began to offer a wide range of possibilities, including improved modeling and simulation, more meaningful visualizations, advanced interaction media, and AI. These new capabilities have led to a radical departure from traditional engineering practices. Indeed, **digital engineering** has become a concrete industrial practice that enables virtual testing of activities at the design stage and, of course, throughout the life cycle of a system. At the same time, complexity has increased dramatically due to global interconnectivity. HSI has therefore naturally become one of the major disciplines to support the management and mastery of this digital shift. As the user interface gradually emerged as a syndrome of 20th-century technology-centered processes, STS designers began to realize that it was possible to

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[3] Artifacts are concrete entities with roles, the context of existence, and resources to support the execution of tasks they are designed for. Any artifact usually has a life, with a birth (i.e., generally linked to an invention), an operational period (i.e., operated for some time), and a death (i.e., it eventually becomes obsolete).

[4] Early office museum, the earliest writing machines, retrieved from the Internet on 22 November 2022: https://web.archive.org/web/20161227181833/http://www.officemuseum.com/typewriters.htm.

include people throughout the life cycle of a system.

For a long time, automation and human error have led technology-centered approaches to view people as problems rather than solutions to emerging critical issues. This view is mainly due to the failure to consider the evolution of operational contexts and the maturity of STSs [6,29,116]. Indeed, eliminating humans from the control and decision-making loops can solve problems when the context is very well specified and covers many expected situations. However, in unexpected situations, humans must solve problems "on their own," but often need the help of more knowledgeable and experienced technological, organizational, and human resources. Our research program approach follows James Reason's statement: "Fallibility is part of the human condition. Although we cannot change the human condition, we can change the conditions under which humans work." [30].

The rest of this article is organized as follows. First, in Section 2, we introduce the reader to the central notions of a system. Then, in Section 3, we discuss the nature of system complexity from two architectural perspectives: system and context (in the sense of situation awareness). In Section 4, we study how to make procedural and declarative knowledge tangible. Next, in Section 5, we explain how the digital twin concept is an appropriate tool for HSI. Section 6 explains why HSI should oversee systems engineering. Then, in section 7, we present the work in progress by our research program on an HSI ontology. Finally, the conclusion section proposes some remarks and perspectives.

2. What do we mean by system? – axioms, properties, and principles

The surrealist René Magritte famously stated, "this is not a pipe," in his painting "The Betrayal of Images," which represents … a pipe (Fig. 1). His work emphasizes that the representation of an entity is not the physical entity itself, but the artist's view of the entity in question. This idea includes both natural[5] or artificial entities. In Magritte's painting, the pipe is recognized by looking at the image, which suggests its structure and function, and the articulation of structure and function: this leads to affordances [31,32].[6] Affordances describe the relationships between people and their environments. For example, a pipe has at least two affordances: its structure allows it to be held appropriately and its function allows for the act of smoking.

Fig. 1. Magritte's pipe representation.

Let's now define the term "system" by first defining a set of axioms.

Axiom 1 states that a system **represents** an entity that can be natural, artificial, or a combination of both. In the engineering world, systems implicitly refer to "machines," whereas physicians typically refer to the "cardio-vascular system" or "human cognitive system." These are not machines! They are biological organs. So, we must have natural and artificial systems, human and machine systems.

Axiom 2 states a system is based on systemic **recursivity**. This is the concept of a **system of systems** (SoS) to refer to the complexity of a system as a set of local subsystems interacting with each other to create an overall behavior [33]. For example, an aircraft can be represented as an SoS, where a wide variety of systems must work together to ensure the viability of a flight. Another example can be found in natural systems, where the brain includes neurons interacting between each other to make emerge consciousness. It is usually thus the interactivity of the subsystems that induces the emergence of the overall behavior.

From an HSI perspective, natural systems can include artificial systems (e.g., a human being can be fitted with a pacemaker or wear glasses), and artificial systems can include natural systems (e.g., a car can include one or more human beings). We usually admit that a human being (or machine) is a natural (or artificial) entity; therefore, a human (or machine) system represents a human being (or machine). It is therefore helpful for HSI to have a systemic representation (i.e., framework or model) consistent for describing humans and machines.

Axiom 3 states that a system can be described by a **structure** (i.e., what it is made of; what it looks like) and a **function** (i.e., what a system does and its operational role). For example, the human heart has a specific structure (composed of atria, ventricles, and cardiac muscle cells) that allows it to pump blood throughout the body (i.e., its function). Similarly, for a machine, a car has a specific shape that will enable it to penetrate the air easily and characterizes its aerodynamics (i.e., one of its functions). Fig. 2 summarizes and develops what has been described above in a graphical form.

Structure determines function, and vice versa. For example, the structure of the human lung, often called the respiratory system, consists of 23 generations of bronchi. Its function can be divided into two functional phenomena, convection between the mouth and the 21st generation and diffusion within the last two generations, where the number of branches suddenly increases exponentially [34]. The human lung is beautifully structured to allow, during inspiration, a rapid transfer of oxygen (convection function) from the mouth to the last generation of bronchi in contact with the blood vessels where the diffusion of gases through the membranes of the alveoli takes place.

An entity has a purpose that is supported **by means**. In conventional technology-centered engineering, technological means are designed first, and operationally tested when (almost) fully developed. Today, digital engineering enables us to co-adapt purpose and means, starting from a purpose (i.e., system's functions), and find out means (i.e., appropriate structures), using HCD methods (see Figs. 12–14 below).

Axion 4 indicates that functions and structures can be **physical** and/or **cognitive**. A "human" as an instance of natural entities can be represented by a "natural system," and a "machine" as an instance of artificial entities can be represented by an "artificial system" (Fig. 2).

Axion 5 states that a system is described from two perspectives:

1) teleologically by its **role**, its **context** of validity, and its **resources** which are systems themselves (Fig. 3); and
2) logically by its process of transforming a **task** into an **activity** (Fig. 4).

A system may have multiple structural and functional parts; since a function can be represented as a function of functions and a structure as a structure of structures, a system can be represented as a SoS. A function is a function of functions through its resources, which can be systems

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[5] The term "natural entity" is used here instead of "living entity," which might be more appropriate in the perspective of "human" versus "non-human" [108]. However, the distinction made here considers natural entities to include both human and non-human living entities, such as people, plants and animals, as opposed to machines.

[6] Affordance is a neologism proposed by the American psychologist James Jerome Gibson. It is a human or animal faculty that guides behavior by perceiving what the environment offers in terms of potential actions.

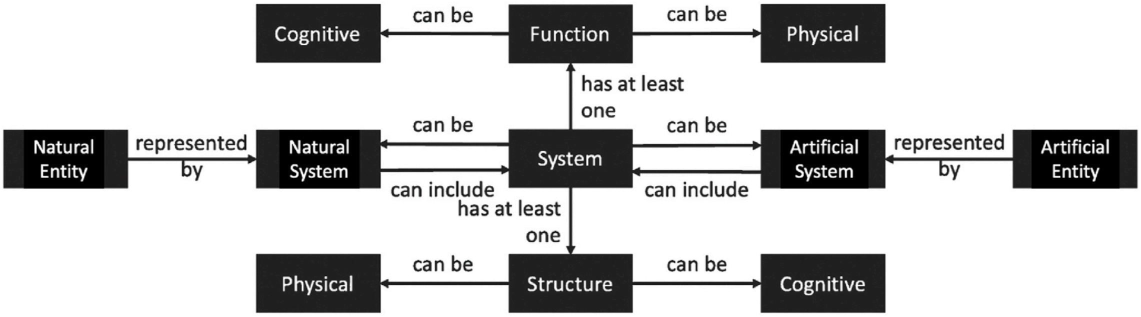

Fig. 2. A human or a machine represented as a system can be defined by its structure and its function, which can be cognitive and/or physical.

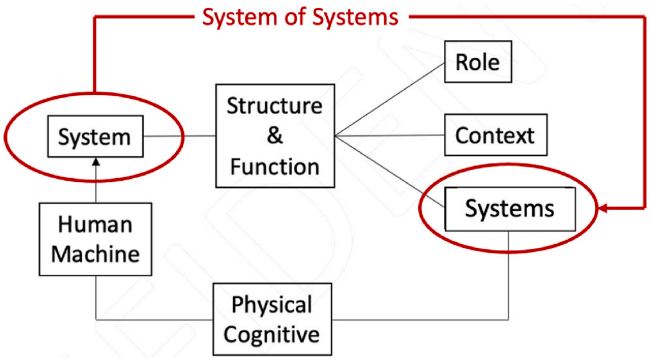

Fig. 3. An integrated socio-technical system ontology.

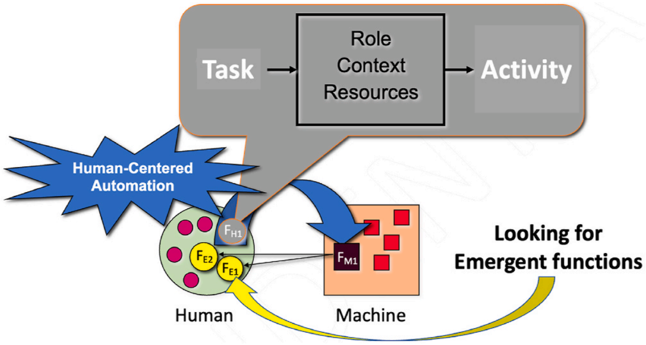

Fig. 4. Emergence of cognitive functions when a human function is transferred to a machine, and the human uses it (human-centered automation).

themselves (Fig. 3). Therefore, we can define an STS ontology in terms of role (which describes the logical transformation of a task into an activity), context of validity, and resources (which are systems themselves). This recursive property of a system defines the SoS concept (the teleological aspect of a system). Fig. 3 integrates the content of Fig. 2 with these teleological aspects, explicitly showing the nature of a system of systems.

Allocating functions to an SoS is a crucial process challenging to manage because systems are **defined recursively** (i.e., a system is an SoS). Function allocation is also tricky because several systemic dimensions must be incrementally articulated: the role of the system (i.e., what its structure and function are for), the context of the system's validity (i.e., where and when the system has a proven utility); the subsystems as human systems and/or machine systems, the physical and/or cognitive resources that are systems themselves (i.e., how the system can fulfill its role).

Not only can function allocation be done a priori for all system subsystems but emergent functions (e.g., workaround practices that can be discovered from an activity analysis) and structures (e.g., physical parts that were not initially identified) must be considered. Let us imagine that we automate a machine by transferring cognitive functions from humans to the machine. Fig. 4 shows how human-centered automation is done incrementally (e.g., think of augmenting the human respiratory system with a mechanical ventilator system). It involves transferring a cognitive function F_{H1} from a human to a machine, creating a new function F_{M1}. Using F_{M1}, the human discovers that they need to handle new emerging functions F_{E1} and F_{E2} (e.g., these could be functions of adapting the human to the ventilator system).

The role of the respiratory system is to transfer oxygen to the blood capillaries around the pulmonary alveoli and to expel carbon dioxide to the mouth. The temporal context is defined as follows: inspiration (inhalation) lasts 1–1.5 s and breathing out (exhalation) for 1.5–2 s. Resources are twofold: the lung structure described above (physical) and a control mechanism activated by the human nervous system (cognitive). The task of the respiratory system is to perform its role (i.e., to transfer oxygen to the blood and carbon dioxide back to the mouth). However, it may be times when the activity of the respiratory system is different from that intended for the task. Parts of the lungs may be obstructed, resulting in insufficient oxygen transfer. Ultimately, a ventilation system could be used to help. A new SoS is then defined that combines various natural and artificial systems included in the patient and ventilator. The teleological notion of role is the link between any system and the SoS to which it belongs.

Let's take another example. Let's say you want to drive from city A to city B. Driving is a physical and cognitive function that allows you to move through space and time. This function includes a cognitive system of navigation and a cognitive and physical system of steering. The cognitive navigation system typically involves a Global Positioning System (GPS), an SoS that includes sensors and automated artificial functions to calculate the right trajectory to reach the goal at the right time. Several emergent human cognitive functions result from using GPS (e.g., checking that the trajectory proposed by the GPS works fine). The steering system involves several systems, both on the human and machine sides. One of these systems on the machine side (i.e., the car) can manipulate the steering wheel as a physical system. Another system on the human side (i.e., the driver) may be the ability to steer the car to follow the intended path. It is also possible that the vehicle is equipped with an autopilot that automatically keeps it on the intended direction.

By definition, a system is a resource for another system that uses it internally or externally. Here we find the power of the SoS concept. The notion of context is always associated with the concept of situation and can take several meanings, such as those described in Fig. 7 (see below). Context is usually characterized by various independent variables and complex attributes, ranging from time to space, critical conditions, specific state history, normal, abnormal, and emergencies. In the same way we defined the concept of system architecture, and more specifically the notion of a system of systems, it is useful to define the concept

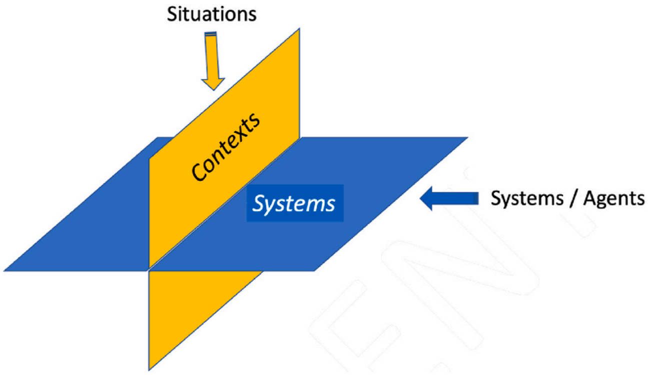

Fig. 5. Orthogonality of systemic and contextual spaces.

of context architecture, and more specifically the notion of a context of contexts. Context is always associated to the notion of persistence (e.g., the context of being at home during a specific period). Indeed, an STS is constantly evolving due to its own dynamics and because its subsystems are adapting. First, humans adapt no matter what! Nowadays, machines are beginning to adapt through "manual" design changes and machine learning algorithms. This adaptation is typically done with two orthogonal spaces that offer the ingredients for the definition of related architectures: system (resource) space and context space (Fig. 5).

There are many layers of nested system resources (i.e., systems of systems) for various contexts. Therefore, in a constructivist sense and extending Piaget's development theory [35], we can speak of **situated resource schemes** (i.e., resources/systems associated with meaningful contexts). Good HSI requires capturing these schemas to develop appropriate technologies, organizations, and people's skills and knowledge that ensure an acceptable balance. Consequently, relevant **principles and criteria**, such as situation awareness, workload, cost,[7] performance, trust, and collaboration, must be developed. They are used and refined during the design and development process of a human-machine SoS.

For example, the letter carrier, considered as a system, can be represented by a role (e.g., delivering letters), a context for that role (e.g., timewise: 8 a.m. to 12 p.m. and 2 p.m.–5 p.m. Monday through Friday; space-wise: The neighborhood to which they are assigned; and in normal conditions); and a set of resources that can be physical and/or cognitive systems, human and/or machine (e.g., for the letter carrier, the physical resources can be a bag to carry letters and a bicycle or a car, and cognitive resources can be their ability to match the address on the letter with the name of the street, the number of the house, the name of the addressee). In abnormal and emergency conditions, the letter carrier may have a different role, be in a different context, and have a different set of resources/systems. For example, they may become a trainer or manager of temporary letter carriers in different time and space contexts.

Designing and operating STSs requires considering various kinds of contextual conditions that include **responsibility**. For example, who is responsible once a system is commercialized? Let's imagine we will be able to develop a fully autonomous car. Who will be responsible if this car is involved in a road accident? How could a system be defined as a legal entity? The responsibility for a system is a matter of system resources with capabilities and limitations. The system's resources are systems themselves. Domain competencies and knowledge characterize capabilities and constraints and are subject to context. Authority sharing between STSs needs to be seriously considered in terms of control (i.e., which STS is in charge) and accountability (i.e., one STS is accountable to another) [36].

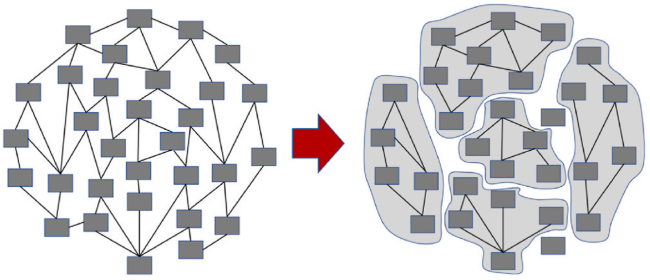

Fig. 6. Example of a system of seven separable systems.

Finally, the acceptability of the system representation must be based on principles. Let's provide a first set of three principles: consistency; tangibility[8]; and usefulness and usability. Since a system is a representation, the first principle of acceptability states that the underlying language must be lexically, syntactically, semantically, and pragmatically consistent. The second principle states that all components and any combination of these system components must be figuratively and/or physically tangible and capable of being accurately identified and manipulated. The third principle states that the system representation must be helpful and useable to make sense of any natural or artificial entity.

3. Architectural complexity and situation awareness complexity

For a long time, a system was considered something isolated from the rest of the world. For example, an isolated system cannot exchange matter or energy with its environment. Therefore, one could typically study an isolated system separately from its environment. In any case, this property of separability of a system, often implicit and, unfortunately, sometimes misunderstood, is crucial (Fig. 6).

Biologists and physiologists have known about separability for a long time [37]. has recently argued that the non-separability of degrees of freedom is the fundamental property underlying consciousness in physical systems,[9] which is a matter of system architecture complexity. In addition, separability is not only a matter of system architecture, but also **context architecture**, where a system can be studied, separate from its environment, in specific contexts that must be articulated. For example, the context architecture of a flight can be decomposed into flight phases: take-off, climb, cruise, descent, and landing. Awareness of interconnectivity and separability between aircraft systems depend on the phase of flight; for example, in normal situations, a pilot needs to be aware of landing gear effectivity during take-off and landing, but not necessarily during other phases of flight. We can see in this example that context architecture is a useful support to situation awareness.

Complex systems comprise many interdependent and heterogeneous (sub)systems (i.e., systems of systems) that interact non-linearly and lead to the **emergence** of specific phenomena. For example, consciousness is an emergent phenomenon of the human brain. Within the

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[7] The notion of cost is not only a question of money, but it could also be related to the involvement of people in terms of safety, efficiency, and well-being.

[8] The concept of tangibility has two meanings [72]: physical (e.g., a physical object can be grasped, it is physically tangible); and figurative or cognitive (e.g., an abstraction or a concept can be understood, it is figuratively tangible).

[9] "The amount of consciousness in a system is determined by the extent of non-separability and the number of degrees of freedom involved. Non-interacting and feedforward systems have zero consciousness, whereas most interacting particle systems have low non-separability and consciousness. By contrast, brain circuits exhibit high complexity and weak but tightly coordinated interactions, which appear to support high non-separability and therefore a high amount of consciousness." [37].

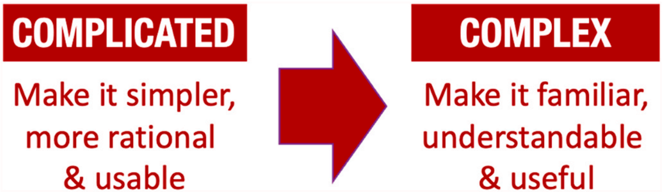

Fig. 7. A systemic way of considering the complex-complicated distinction.

framework of the highly interconnected systems developed today, we must develop methods and tools to identify these emergent phenomena by observing their activity. For example, the overall effectivity of an aircraft can only be assessed with flight testing of the entire system in its simulated environment, even if we can test some of its parts in isolation. The overall connectivity allows us to identify emerging phenomena in a system (e.g., an aircraft flying in specific airspace). Consequently, it is essential to implement and use increasingly tangible human-in-the-loop simulation (HITLS) systems [38],[10] at the earliest stages of engineering design to discover emergent properties and phenomena. HITLS enables to find emergent behaviors and properties of a complex sociotechnical system. At this point, we need to have a clearer grasp on what we mean by complexity.

First, let's analyze the distinction between what is **complex** and what is **complicated** (Fig. 7). A complicated system usually requires many types of expertise to manipulate or manage. We understand a complex system through learning and adaptation. Complexity is a matter of the number of nodes and links between these nodes. Becoming aware of the significant nodes and their various connections may take time. Indeed, familiarity increases the maturity of the practice and decreases the perceived complexity. Instead, a complicated system usually requires simplification.

Second, the structure(s) and function(s) of a complex system must be architected to facilitate situation awareness (SA), that is, the way the system is perceived, understood, and operated (i.e., how to induce what to do next). When considering engineering systems, SA is associated with affordances, which we cannot create but discover from activity. Therefore, HITLS is very useful at the design stage for observing various induced activities. Indeed, SA is a matter of context architecture that typically supports scenario-based design [39].

Mica Endsley introduced the SA concept in complex systems long ago [40,41–43]. We recently proposed a description of situation awareness (Fig. 8) by making appropriate distinctions based on various meanings of the situation concept and awareness functions [44].

The real situation is impossible to capture because it involves too many entities. We have access to the available situation from external sensors. Still, there is no guarantee that it corresponds to the situation perceived by internal sensors (e.g., central vision or hearing systems). Once the perceived situation is interpreted, a meaningful situation is captured and used to infer a projected situation (i.e., what to do next). These situations are influenced by the expected situation that, in some cases, can distract or distort the perceived situation. The desired situation has a direct impact on the interpretation and projection processes. Overall, the background situation available in long-term memory influences all cognitive functions.

System complexity increases when interactions between humans and machines become more cognitive. Specifically, cognitive functions can be **event-driven** or **goal-driven**. Using the multiple meanings of the concept of a situation in the cognitive situation awareness model, shown in Fig. 8, an event-driven interpretive cognitive function is typically based on predicting the perceived situation concerning the expected situation, which leads to a short-term reactive behavior. In contrast, a goal-driven interpretive cognitive function generally anticipates possible futures by considering perceived and expected situations and ensures that subgoals are correctly achieved. Therefore, successful behavior is achieved when cognitive functions are flexible enough to switch from goal-driven to event-driven. This switching process is referred to opportunistic.

In a life-critical STS, safety and efficiency are generally ensured by operational procedures that automate people and what is usually called "automation," which automates machines. Operating procedures and automation tend to rigidify work practices because they are defined a priori in expected situations. All is well if the current situation remains within the context of the validity of procedures and/or automation.

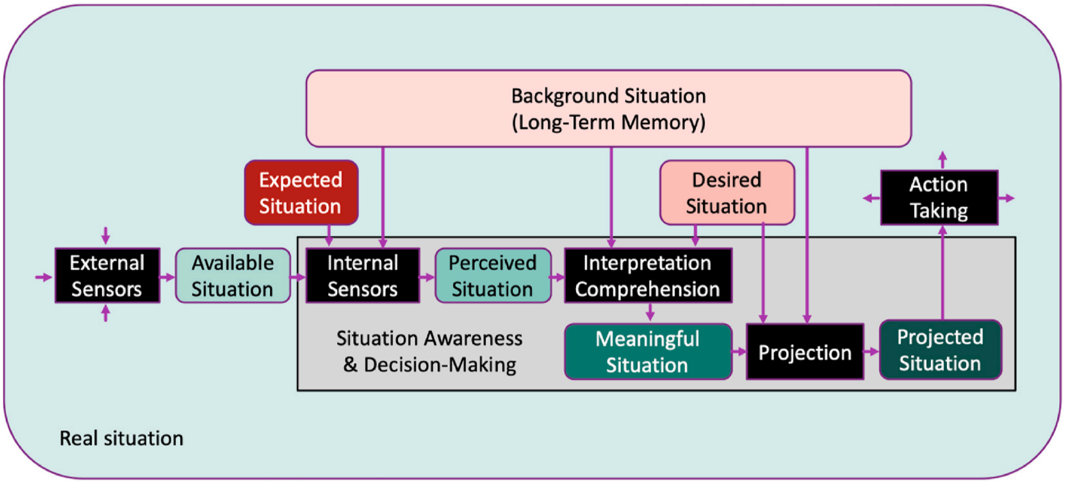

Fig. 8. Various interconnected human-centered meanings of the situation concept.

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[10] With the rise of digital engineering, we prefer to directly put real humans in the loop whenever possible instead of simulating digital human models [107] to support better the opportunity to discover emergent behaviors and properties of sociotechnical systems which lead to the definition of emergent functions and structures.

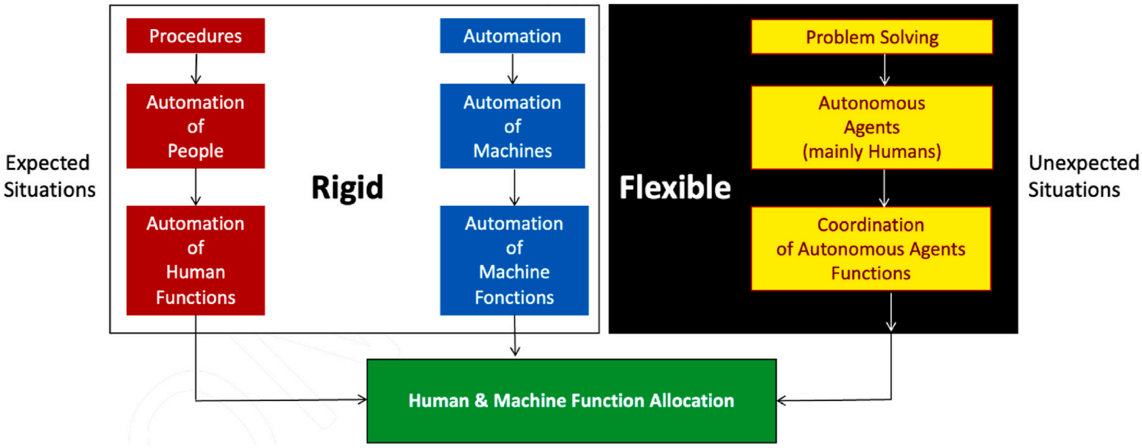

Fig. 9. Rigid and flexible function allocation.

However, if the current situation is unexpected, the procedures and automation become invalid and dangerous. Another strategy is needed: instead of following procedures or monitoring automation, we need to solve a problem. Problem-solving is usually done by humans and supported by a coordinated team of people and machines. It requires flexibility to consider possible futures. Therefore, **procedure-following** and **automation-monitoring and control** primarily involves event-driven functions, constantly based on predictions and deduction inference.[11] In contrast, problem-solving involves goal-driven functions based on creativity, management of possible futures, and abduction inference[12] (Fig. 9).

This rigidity-flexibility framework influences how we see the environment.[13] Procedures and automation are defined in each context, which assumes a close world. In contrast, problem-solving takes place in an **open world**. Therefore, distinguishing between a closed world and an open world is essential when studying system complexity. Automation assumes, often implicitly, a closed world. In contrast, autonomy should consider an open world that we need to consolidate using a variety of our research program support, i.e., technology that supports flexible problem-solving flexibility. If we take up the TOP model again, we cannot limit flexibility to technological support but expand to organizational support and human skills.

In summary, the complexity of systems is not only a matter of structural complexity (i.e., networks of highly interconnected objects) but also of context-dependent functional complexity, intimately influenced by the complexity of situational awareness, which involves a wide variety of cognitive and physical functions of humans and machines, which include procedure following, automation monitoring, and problem-solving.

4. Making procedural and declarative knowledge tangible

The aeronautical industry has significantly contributed to the development of Systems Engineering (SE). First, the mechanical development of airplanes showed the importance of systems thinking in terms of prostheses, since humans cannot fly, but they can be equipped with an aircraft that allows them to fly. This streamlined the concept of an SoS combining, for example, thrust, drag, and lift capabilities. Then, automation and software emerged, and physical prostheses now exist alongside cognitive augmentations. Aircraft have become increasingly automated through the development of embedded systems, such as autopilots, flight management systems, and collision avoidance systems. These systems are individual entities that have recently led to the concept of a **cyber-physical system**[14] (CPS): larger physical SoSs with cognitive capabilities enabling an intelligent, connected world [45].

Engineering has been using the concept of a system for a long time, but it was not until the 1930s that Ludwig von Bertalanffy developed the "General Systems Theory" [46]. The objective of this general theory was to find explanatory principles of the universe considered a system with the help of which one could model reality. Bertalanffy asserts that there are systems everywhere. This statement fits very well with the first axioms of this article (i.e., a system is a representation of an abstract and/or concrete entity, natural or artificial). Subsequently, systems science has been rigorously studied over the years and gradually blended with SE, making systems thinking a significant area of investigation [47–52]. The emergence of HSI brought the human element within SE [53].

Interestingly, the life and social sciences, as well as engineering sciences, have cross-fertilized each other. Although the French physician, physiologist, and epistemologist Claude Bernard (1813–1878) did not invent the term, he created the concept of homeostasis. Subsequently, American physiologist Walter Cannon (1871–1945) consolidated and clarified the concept of homeostasis, which American mathematician Norbert Wiener (1894–1964) and British psychiatrist William Ross Ashby (1903–1972) extended to the idea of cybernetics [54,55]. Cybernetics formalized the concept of homeostasis, feedback, and system dynamics. This cross-fertilization has led to models and theories of automatic control that have fueled developments in SE and the study of complex adaptive systems. These models and theories have been beneficial in the development of CPSs (e.g., highly automated aircraft, robotic systems, intelligent buildings, and semi-autonomous vehicles). What is becoming more apparent today is the convergence of systems engineering and AI; more specifically, systems of systems in SE [56,57] and multi-agent systems in AI [58] have much in common.[15]

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[11] Actions are deduced from a set of rules and perceived situations.

[12] Possible futures are anticipated, and actions to be taken try to demonstrate that they will lead to these possible futures. Abduction inference intimately relates to risk-taking [109].

[13] Dealing with the environment is often a matter of cultural factors in addition to the technology-organization-people triptych. Specifically, once a technology is developed and operated (e.g., an airplane), it depends on the **culture** of the people who operate it.

[14] Cyber-physical systems combine computer elements and physical entities that can interact with humans in many ways.

[15] A step further, Humberto Maturana, a Chilean biologist and philosopher (1928-present), developed with his student Francisco Varela, a biologist philosopher, and neuroscientist (1946–2001), the concept of autopoiesis, which is an extension of the concept of homeostasis. Autopoiesis refers to systems that can keep their internal environment and reproduce themselves. It is applied in biology, chemistry, systems science, and sociology.

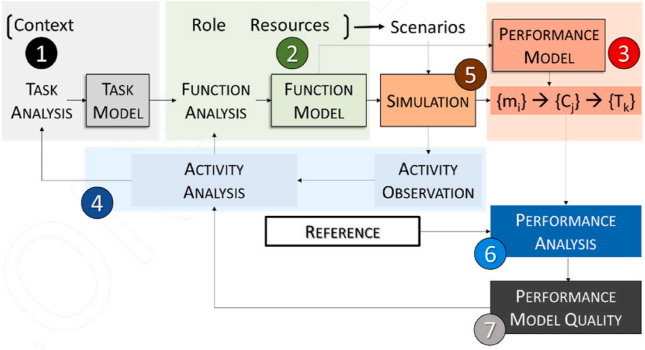

Fig. 10. Methodology for performance assessment of a multi-agent system.

On the industry side, although the first autopilots were available in the 1930s [59], the development of information technology during the 1980s allowed for the long-term development of onboard aircraft systems. There has been a shift from analog systems performing simple tasks to **digital systems** handling increasingly complex functions. These embedded systems, such as flight management systems, use sophisticated algorithms that are more interconnected (i.e., they give rise to SoS). This evolution induces changes, such as the shift from controlling low-level parameters to managing complex systems. This double shift from analog to digital and control to management radically changed the pilot's job.

Safety, efficiency, and comfort requirements drove the development of embedded systems, which have often been stacked, resulting in operational complexity. Indeed, while many embedded systems are beneficial and useable individually when stacked without being adequately integrated, they involve multiple and complex tasks that are difficult to manage. This HSI problem requires a systems approach to analyze the functions and make them meaningful and useable. Therefore, we have developed **PRODEC**, a method that supports the discovery of hidden functions and structures progressively incorporated into the resulting system (Fig. 10).

PRODEC begins with a task analysis that enables the building of a task model (the procedural part [point 1 in Fig. 10]), followed by a function analysis that allows the construction of a functions model (the **declarative** part [point 2 in Fig. 10]). These analyses allow for describing system resources and identifying function's roles within a domain-specific context. Human-in-the-loop simulations [point 5 in Fig. 10] can be performed, and human and machine activity can be observed, enabling an activity analysis. This activity analysis [point 4 in Fig. 10] impacts the function model. At each iteration, a performance analysis is performed based on a performance model [point 3 in Fig. 10], which leads to a performance analysis [point 6 in Fig. 9] that is evaluated using performance quality measures that enable to build a performance quality model [point 7 in Fig. 10]. High-level meaningful metrics $\{T_k\}$, such as "operational performance," "trust," and "collaboration," enable to assess of the distance between expected $\{T_k\}$ (i.e., prescribed task) and effective $\{T_k\}$ (i.e., activity), depending on criteria $\{C_j\}$, such as "efficiency," "effectivity," "transparency," and "flexibility," that themselves depend on low-level measures {mi}, such as "processed information," "verified information," "interaction time," and "quantity and quality of machine feedback."

The design of an artifact (e.g., a machine) consists of defining its structure and its function. Each structure and function can be described in both abstract and concrete terms. The SFAC model (*Structure/Function* versus *Abstract/Concrete*) provides a dual articulation (i.e., abstract and concrete) between the structure and function of an artifact (Fig. 11) as follows:

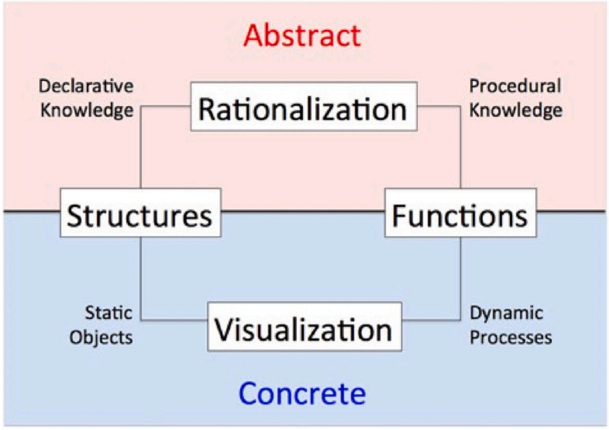

Fig. 11. The SFAC model [60].

- declarative knowledge (i.e., abstract structures);
- procedural knowledge (i.e., abstract functions);
- static objects or systems (i.e., concrete structures); and
- dynamic processes (i.e., concrete functions).

The abstract part is a rationalization of the system being designed (i.e., a knowledge representation), which can be formalized by a set of concepts linked together by relations. We can call this rationalization an ontology, a semantic network, or a concept map. It can be a tree-like hierarchy in the simplest case or a complex concept graph in most cases.

The terms "declarative" and "procedural" refer to the "know-what" and the "know-how" respectively. In cognitive psychology, they describe human memory [61], and their relationships have been studied in developmental psychology [62]. Declarative memory includes facts and defines our semantics of things. Procedural memory includes skills and procedures (i.e., how to do things). We can think of declarative memory as an explicit network of concepts. Procedural memory can be thought of as an implicit set of skills (i.e., know-how). We assume that the cortex comprises declarative and procedural memory that evolves through learning. The former is generally stored in the temporal cortex of the brain. The second is stored in the motor cortex of the brain. The relationships between conceptual (declarative) and procedural knowledge have also been studied in mathematics [63,64].

According to the SFAC model, at the design stage, the concrete part is usually represented using *Computer-Aided Design* (CAD) software, which allows the designer to generate 3D models of various system components being designed. These 3D models include static objects and dynamic processes that visualize how the designed components work and are integrated. Today, they are 3D printed, which gives a more concrete grasp of the components being built and their possible integration: we would say they are physically tangible. Testing takes place at each stage of the design process by examining the concrete parts and their abstract counterparts (i.e., their rationalization and justifications). Rationalization is a means of making designed systems figuratively tangible or cognitively tangible.

The SFAC model is typically developed as a mediation space that design-team members can collaboratively share, modify, and validate. SFAC allows the design team to document the design process and its solutions better. The concept of an active design document (ADD), initially developed for traceability purposes, helps streamline innovative designs and progressive formative evaluations [65,66]. The SFAC model was the basis of the SCORE system used as a mediation aid for a light water nuclear reactor design team in their collaborative work and project management [67].

Based on the SFAC model, the PRODEC method is proceduralized as follows [6]:

1. Identify and review all tasks necessary to achieve the various objectives.
2. Describe them in the form of BPMN[16] graphs (procedural scenarios).
3. Identify meaningful functions in the form of role (associated with tasks and objectives), context and associated system resources (declarative configurations).
4. Describe and refine relevant elicited system resources in terms of structures and functions (based on the CFA[17] formalism and the AUTOS Pyramid framework[18]).
5. Iterate until a satisfactory solution is found.

PRODEC is currently applied extensively throughout several HSI projects: in air combat operations, oil and gas tele-robotics, remote maintenance, and health system [9,68,10,69]. It has been transversely developed and tested as a generic model-based HSI support method.

5. From modeling and simulation to digital twins?

For designing the architecture of complex systems, *Model-Based Systems Engineering* (MBSE) [70] has contributed to the development of several models and notations, such as SysML [71] and Arcadia/Capella.[19] However, these frameworks and platforms are based on something other than human and organizational factor considerations, leading to a constraining rigidity when STSs need to be represented and modeled. For this reason, an HSI ontology needs to be further developed to provide more **flexibility** in the analysis, design, and evaluation of STSs [29]. In a highly interconnected digital SoS, the emergence of hidden properties must be carefully examined concerning tangibility issues, and supported by a model that can be simulated, the digital twin. We call this approach **model-based human systems integration** (MB-HSI) [7], which leads to two main issues that require better understanding in our increasingly dematerialized society: tangibility and emergence.

We can implement domain models (e.g., aerodynamic, structural, embedded system models) in virtual prototypes and consider human factors very early in the design process of a complex system. The counterpart is the virtuality of human-in-the-loop simulations that allow the observation and analysis of human activity and the progressive discovery of emergent properties of the STS under development. Therefore, we must evaluate the distance to reality. In contemporary HSI, tangibility is the concept that gives meaning to this distance [6,72]. Tangibility metrics are developed around five main concepts: complexity, maturity, flexibility, stability and resilience, and sustainability [72].

Technology-Centered Engineering (TCE) has long been the standard for engineering, requiring the development of user interfaces often too late to adapt human operators to machines. This practice is primarily due to how commitments on system resources are made, mostly too early in the design and development process, leaving very few alternatives for a later redesign in later phases of a system's life cycle (Fig. 12). This early commitment to system resources (red curve) decreases design flexibility (blue curve). In addition, people learn about the system as they operate it (green curve).

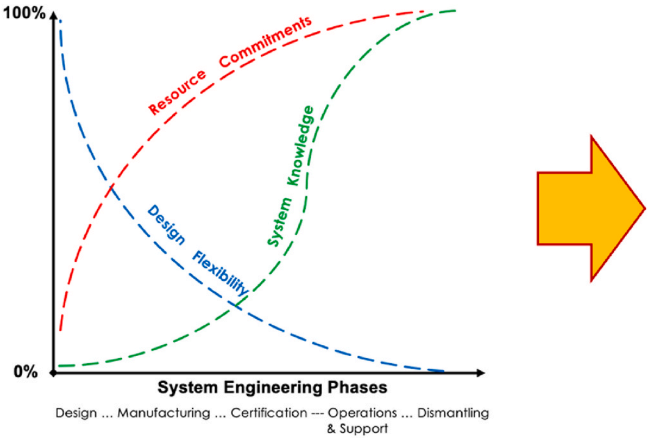

Fig. 12. Technology-centered engineering.

In contrast, HCD based on virtual prototypes (i.e., *Virtual HCD* or *VHCD*) allows knowledge about the system under development (green curve) to be gained much earlier than before (Fig. 13). Design flexibility is maintained at a very high level for a more extended period (blue curve), and there is no need to commit system resources as early as in the case of TCE.

Now, if we extend the VHCD approach to the entire life cycle of a system (Fig. 14), the modeling and human-in-the-loop simulations could be recorded as several software-based ADDs that allow for what-if testing at any given time [65]. These ADDs are digital twins (DTs) of the system under development and operation [73,74–76].

DTs can be improved through experience feedback and provide an organizational memory of the system's history. Ultimately, DTs could be helpful as virtual assistants for collaboration with human operators: a rather old topic that needs to be revived [77]. This is a helpful way to streamline and build human-machine teams [78–80].

Recently, a precise definition of a digital twin has been developed, that is, "A digital twin is 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

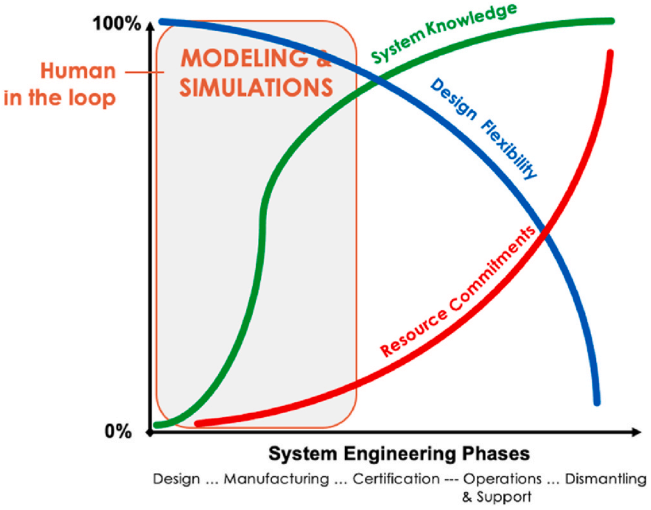

Fig. 13. Human-Centered Design (TCE) approach. (HCD) approach.

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[16] BPMN is a standard for business process modeling and a language for obtaining procedural knowledge [61,110] and formalizing it graphically [111, 112]. BPMN is based on a flowcharting technique adapted to the creation of graphical models of process operations, like UML (Unified Modeling Language) activity diagrams. BPMN is procedural (i.e., it allows the description of procedural information with different graphical elements in the form of scripts, episodes, sequences, etc., which mixes the modes of interaction of agents with each other – it is a program or a routine in the computer sense).

[17] Cognitive Function Analysis (CFA) is a method for generating declarative (functional) knowledge [113,114]. It has now been extended to Cognitive and Physical Structures and Functions Analysis (CPSFA).

[18] The AUTOS Pyramid was described in detail in the introduction to the Handbook of Human-Machine Interaction [115]. It should be noted that the term "user" is used in this model to denote a human interacting with a machine, itself denoted as an "artifact." We keep these denotations to ensure the continuity of the AUTOS model, designed in the context of human-computer interaction and used here in the context of human-system integration.

[19] https://www.eclipse.org/capella/arcadia.html.

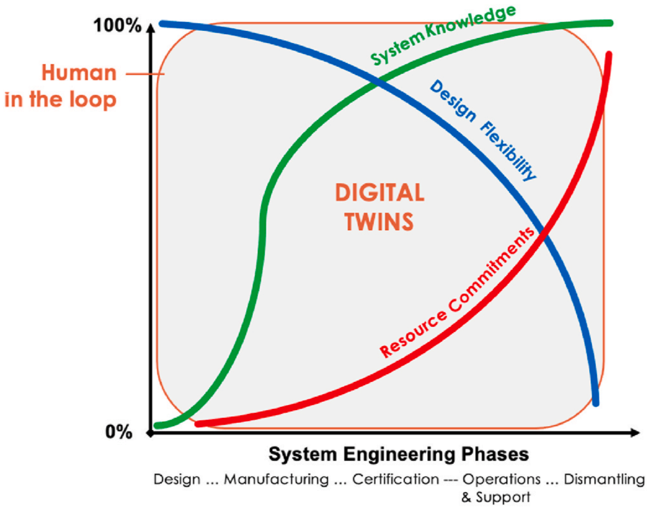

Fig. 14. Human-centered design supported by a digital twin during the whole life cycle of a system.

system." [81]. This concept of DT has been used in a research effort in the oil-and-gas sector to improve situation awareness for human operators. The same concept is used for remote helicopter engine maintenance (Lorente et al., 2022).

Let's use the simple digital twin ontology shown in Fig. 15 [82]. We will make a distinction between **Predictive** and **Explanatory DTs.** Predictive DTs are highly tested, simple digital analogs defined in a limited context, short-term, rigid, and focused. Explanatory DTs are characterized by an ontology of the relevant domain, longer-term, flexible, and generic, for analysis, design, evaluation, and documentation.

Since a digital twin is a system, it inherits two properties: **structure** and **function**. Both structure and function must be represented and visualized to allow the assignment of functions to various appropriate structures.

A digital twin cannot only be considered as a static entity, but also as a dynamic, even living organism that can evolve progressively by integrating **experience feedback**. It supports system performance at the design/development and operational levels, as well as having a **traceability** system that allows one to explore the design history, understand changes, and as a result make appropriate decisions. A digital twin supports **logistics** and, more specifically, the system's documentation throughout its lifecycle, which is a beneficial, active documentation for supporting VHCD.

Documenting is a design process, and designing is a documentation process! Today, digital twins play the role of technical and operational documentation when they can explain what they do [83]. In cognitive science, we use terms to make concepts explicit. By analogy, an explainable digital twin makes the actual system it represents explicit (i.e., it can provide on-demand explanations of how the system is designed and operates). A digital twin allows, for example, hypothesis testing. Furthermore, it can be used to improve the why (i.e., constituting an organizational memory of the evolution of life cycle knowledge) and the how (i.e., constituting a user interface to improve usability) of the system it represents.

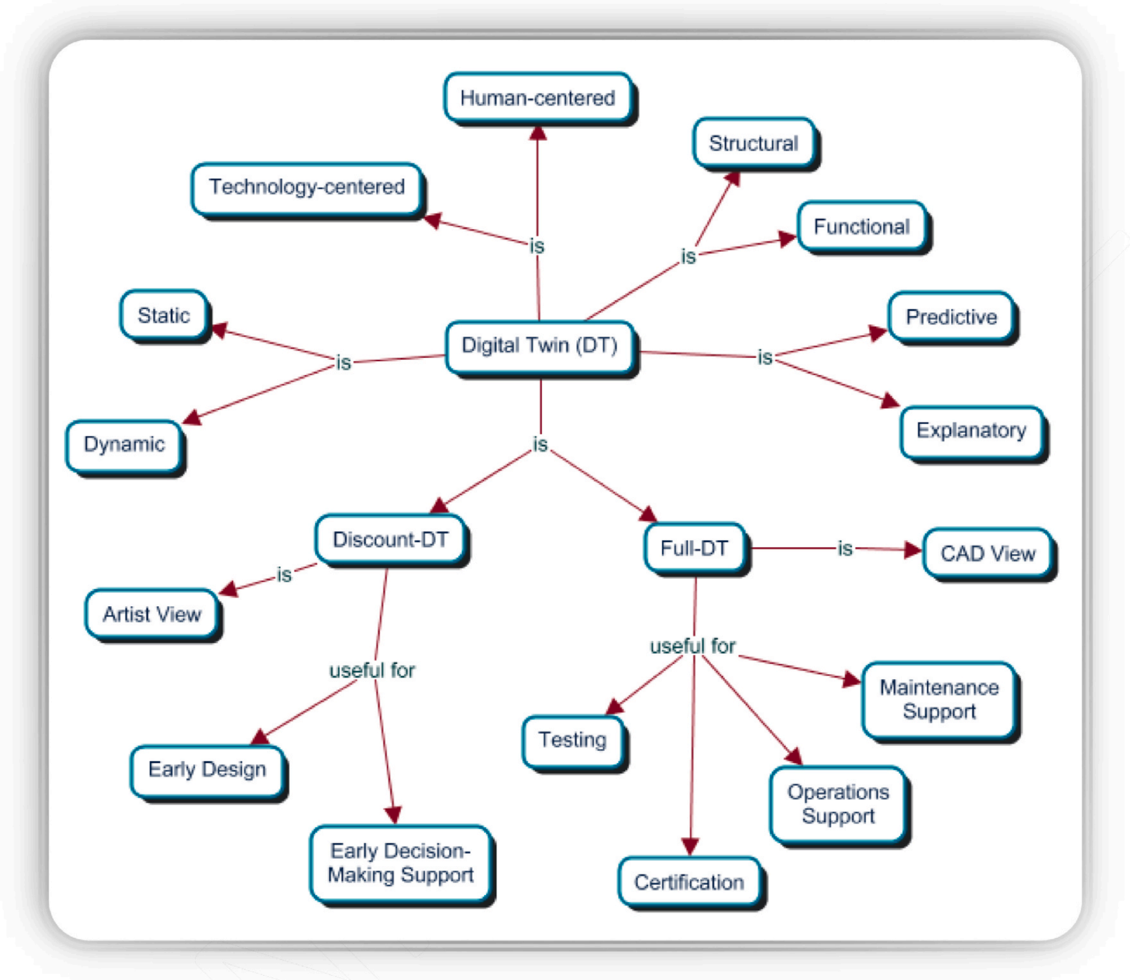

Fig. 15. Digital Twin definition and properties [82].

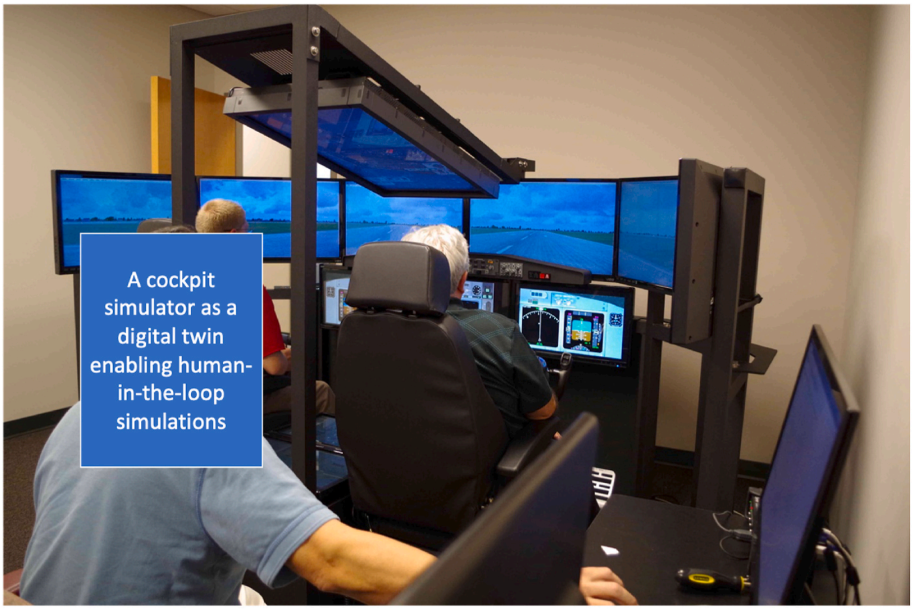

Fig. 16. An aircraft cockpit simulator as a digital twin of digital twins (Photo: courtesy of HCDi, 2017).

As a first step in the design process, using the **discount DT** may be helpful. A discount DT has minimal significant components and entities, useful for representing the system in question [84]. Although the design thinking method [85] can be helpful at this stage, other methods and tools exist for analyzing, designing, and evaluating a system under development. This often involves using this type of digital twin as a medium for visualization, human-in-the-loop simulation, business analysis, emergent function discovery, creativity, modification, and validation among others.

Full DTs can be used when development is sufficiently advanced (e.g., full-flight simulators). At this point, formative evaluation can be used to suggest appropriate modifications. This approach requires scenario-based design and agile design and development. Summative evaluation is the process that allows validation and then certification of the system being developed. Full DTs can also be very helpful in supporting operations, performance, and maintenance, for example. As an example, the HCDi[20] team has developed and operated two commercial aircraft simulators in collaboration with ESP,[21] Airbus 320 and Boeing 737 (Fig. 16), which were used to support human-centered agile development of embedded systems, such as the *Onboard Weather Situation Awareness System* (OWSAS) [86] and a stall avoidance system [87].

Therefore, by augmenting an existing digital aircraft twin (i.e., a flight simulator) with digital twins of embedded systems, we have de facto created an SoS: a digital twin of digital twins. These digital twins can be very sophisticated and highly interconnected. For example, through active Internet links, we connected our HCDi simulators to weather information systems and air traffic information systems. This type of interconnectivity can be very complex, but it effectively improves operational tangibility. Therefore, we developed a multidisciplinary experiment that led to a constant redefinition of various mandatory terms and concepts for excellent interoperability of the global digital twin, supporting our HCD experiments [88]. Indeed, the languages used by pilots, air traffic controllers, and engineers may differ and must be adapted for better mutual understanding. It is like defining a music theory that all musicians can share in an orchestra [6].

In addition, as designing and developing new onboard aircraft systems, new terms, and concepts emerged from our observation of pilot's activity flying simulated aircraft. For example, we discovered new ideas of strategic trajectory planning during the definition and implementation of virtual OWSAS prototypes. We could not have found these emergent properties without the corresponding digital twin simulator (Fig. 16), which we have continuously improved by incorporating emergent features into OWSAS.

6. HSI must oversee systems engineering

Very often, people confuse HSI and user interface design as corrective ergonomics, a practice originating in the 20th century that still endures. However, there are some perspectives that believe it is gradually disappearing. Why? For a long time, engineering came first, and HFE came second (i.e., once a machine was developed, user interfaces had to be designed to adapt end-users to the machine). Nowadays, it is possible to have a different approach. Digital engineering allows humans to be put in the loop and carry out tests much earlier than before (i.e., VHCD) and enables the discovery of emergent behaviors and properties of the sociotechnical system being developed. The VHCD process uses these aspects in an agile way through a series of tangibility-based formative evaluations. The resulting VHCD approach dictates that HSI oversees SE, not the other way around. Failure to do so reverts to the previous practice of having to create user interfaces once the machine is developed.

Since the beginning of humanity, human beings have developed artifacts motivated by the expression of aesthetic and/or functional requirements, for example. Whether these artifacts were physical (e.g., paintings, knives, and houses) or cognitive (e.g., languages, songs, and regulations), various technologies have been developed. Today, we are immersed in massive **digitalization** and AI software. AI technology supports multiple fields, such as data science, multi-agent systems, case-based reasoning, vision systems, natural language processing, and robotics. All these domains require systemic representations and algorithms. From an HSI perspective, AI poses several operational challenges, such as human-machine teamwork, trust, and collaboration, which in turn pose design challenges, such as identification and allocation of appropriate functions [89,90], as well as the early discovery of emergent functions and structures [91]. This type of exercise is highly transdisciplinary and requires a well-coordinated multi-skilled team.

NASA has been and still is very active in the development of HSI

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[20] Human-Centered Design Institute of Florida Institute of Technology, Melbourne, Florida.

[21] Engineering Support Personnel, Inc. (ESP), Orlando, Florida.

research and innovation work; let's mention the NASA HSI Practitioner's Guide (2015),[22] recently updated as the NASA Human Systems Integration Handbook [92], which provides guidance, methods, and tools for the entire NASA community and considers that, in HSI, the human "refers to all personnel involved with a given system, including system owners, users/customers, operators, maintainers, assemblers, support personnel, logistics suppliers, training personnel, test personnel, and others." Concurrently, the APA Handbook of Human Systems Integration has been published and is aimed at a broader engineering community. It provides "specific knowledge about human considerations in systems design." [93]. It explicitly associates human performance with the many components of a system that interact with each other. Although this handbook provides a Human Factors and Ergonomics (HFE) historical overview of the field, let's propose a more systemic approach to HSI in which systems are not only machines but include people, which leads to a representational meaning of the concept of system. This approach is consistent with what is currently discussed, developed within the INCOSE HSI Working Group, and produced in HSI Primer Volume 1 [94].[23]

With the addition of AI-based connectivity, information and transportation technologies bring new system resources with their **capabilities** and **limitations**. We can find almost any type of information on the Internet. We can go almost anywhere we want on planet Earth. We can even optimize our smartphones and focus on our profiles to find contextualized information and study for our next vacation. We can do things ourselves that in the recent past required the help of professionals. We have built and used very sophisticated system resources that extend our capabilities and remove some of our limitations. However, these digital resources also come with other kinds of constraints. We are constantly forced to use them, nurture them, and make them learn from us so that they are more efficient, accurate, useable, and ultimately helpful. These new types of connectivity also contribute significantly to the deterioration of planet Earth with increasing production of pollution generated by servers, as well as land, air, and sea transportation. Therefore, HSI should deal not only with the company's targeted production in terms of a targeted product (e.g., aircraft, computer network, social network) but also with the various peripheral systems that are impacted by the product at stake, both during the development and manufacturing period and during operations of the product itself. This **regulatory mechanism** must be defined, implemented, and used to monitor compliance with established rules.

SE has long been a technology-centered discipline. Modeling languages, such as SysML [95–98], have been developed with this in mind. In practice, while they manage to keep pace with changing technological requirements, they need to consider human factors. This is why HSI recently expanded to focus on human needs and, more specifically, on human functions and structures throughout the life cycle of any STS. For example, responsibility, authority, management, and accountability have become critical issues from a human-machine teamwork perspective. If not addressed early enough in the life cycle of an STS, unpleasant surprises can arise during operations. Therefore, since digital engineering allows it, HSI should drive system engineering as early as possible in the design process. HSI methods are now recognized for increasing the understanding of complex socio-technical systems [2]. The HSI domain should drive the design and development of complex socio-technical systems. Recent developments in air combat multi-agent systems and oil and gas robotics show that HSI delivers remarkable results in this direction [9,10]. These experiments and other projects on the remote maintenance of helicopter engines using digital twins [68] and model-based HSI of semi-autonomous railway systems [99].

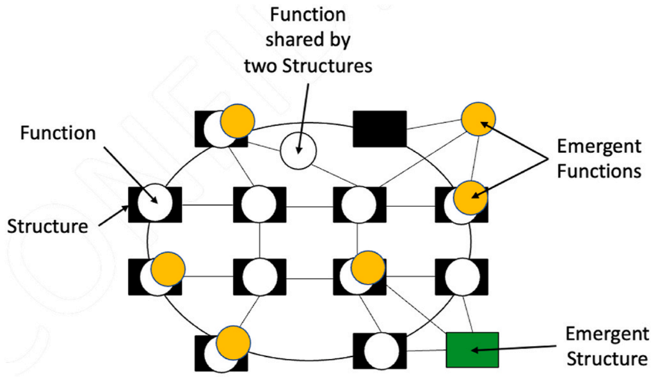

Fig. 17. A human-machine system of systems.

A human-machine SoS comprises a structure of structures (i.e., the system architecture) where functions of functions are allocated. In Fig. 16, structures are represented by black rectangles and functions by white circles. Function allocation can be initiated a priori using domain knowledge at design time. Several structures can share some functions, and a structure could have several functions. However, when the human-machine SoS is effectively operated, emergent functions start to be discovered (yellow circles in Fig. 17) and can be incrementally incorporated into the SoS. In addition, emergent structures could be found during operations (green rectangle in Fig. 17). These structures must be added to the initial or current system architecture.

STSs are necessarily complex, first because humans are complex. This type of complexity is challenging and often only possible to understand and consider a priori with operating the global system. As a result, technology-driven models and assessments need to integrate humans with human-in-the-loop simulation tests properly. **Flexible** system representations are necessary to progressively assimilate and accommodate emergent functions and structures in Piaget's sense [100]. Piaget described children's cognitive development using this epistemic model that involves cognitive processes of assimilation and accommodation at different stages of their lives. In the same way, it is considered that an STS of systems starts with an organized structure of structures (i.e., an architecture) and evolves through different stages by assimilating new functions, which momentarily create an imbalance and are accommodated to restore a new balance. This adaptation mechanism is crucial when humans are involved.

The cross-fertilization of engineering and social sciences is gradually improving what HSI is. HSI requires anthropological approaches that combine experience and creativity (that is, most of the time, contradictory concepts and processes), as well as a solid ontological framework that allows for the rationalization of the most appropriate knowledge that can be elicited.

7. Toward an HSI ontology

The problem of developing an ontology of HSI raises the question of the term HSI itself. Is HSI a good denotation for the field and corresponding emerging discipline? HSI could have been called "systems integration" since systems can be humans, machines, or a combination of both. Still, it is essential to include the term "human" to affirm the importance of people in a human-machine world. Another definition could have been "human-machine integration," but this denotation does not emphasize the systems approach. HSI definition is, therefore, recursive because systems include people. Finally, "integration" is essential as it provides the holistic nature of HSI.

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[22] https://ntrs.nasa.gov/api/citations/20150022283/downloads/20150022283.pdf.

[23] INCOSE HSI Primer proposes the following HSI perspectives: Human Factors Engineering, Social, Cultural & Organizational Factors, HSI Planning, Integrated Logistics Support (ILS)/Maintenance, Workforce Planning, Competencies/Professionalism, Training, Safety, Occupational Health, Sustainability, Habitability of the Designed Environment, Usability, and Comfort/UX.

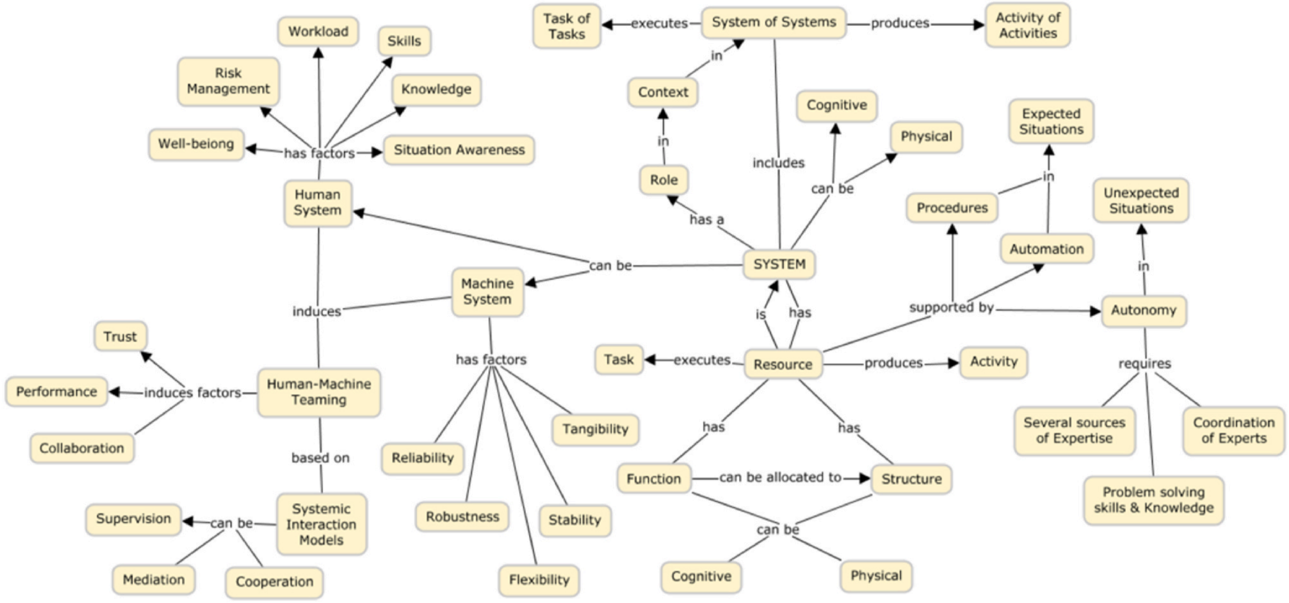


Fig. 18. An HSI ontology under development.

At this stage, it is essential to have a working definition of ontology [101]. It is commonly accepted that ontology is a branch of philosophy that generally questions the meaning of the word “being.” The question “What is being?” must be laid. Focusing on HSI, the corollary questions are, “Does HSI exist by itself?” “What is its definition?” “What are its properties?” “Could emergent properties and behaviors be identified at the time of operations?” “How can an STS be described in terms of interrelated concepts?” And so on.

What has been presented and discussed so far shows the difficulty of building an HSI ontology. Several key concepts and notions have been defined, sometimes deviating from those currently used in SE (e.g., the idea of the system itself). The simple STS ontology shown in Fig. 4 should allow us to build a more detailed account. A deeper HSI ontology should be based on the following points:

- Human and machine functions and structures, and their appropriate combinations, have physical and cognitive representations, with the knowledge that there are potential allocations of rigid function (i.e., taking the form of operational procedures used by people and/or machine automation) and flexible (dynamic) function allocations (i.e., supporting problem-solving in the case of unexpected, rare, or unknown situations).
- The life-cycled evolution of an SoS is impacted by the identification, assimilation, and accommodation of emergent functions and structures, knowing that each system has a role that connects it to the SoS to which it belongs, is valid in a specific context, and has a set of valuable and useable resources that are themselves systems.
- The concept of a digital twin is the contemporary account for technical and operational documentation of the system being designed, developed, and operated. Its tangibility is crucial as it supports situational awareness, decision-making, and action-taking in engineering design and operations times. We can express the distinction between the digital twin and physical twin in terms of virtual STS, which enables human-in-the-loop simulations that support virtual human-centered design, versus real STS, which helps provide experience feedback during operations.

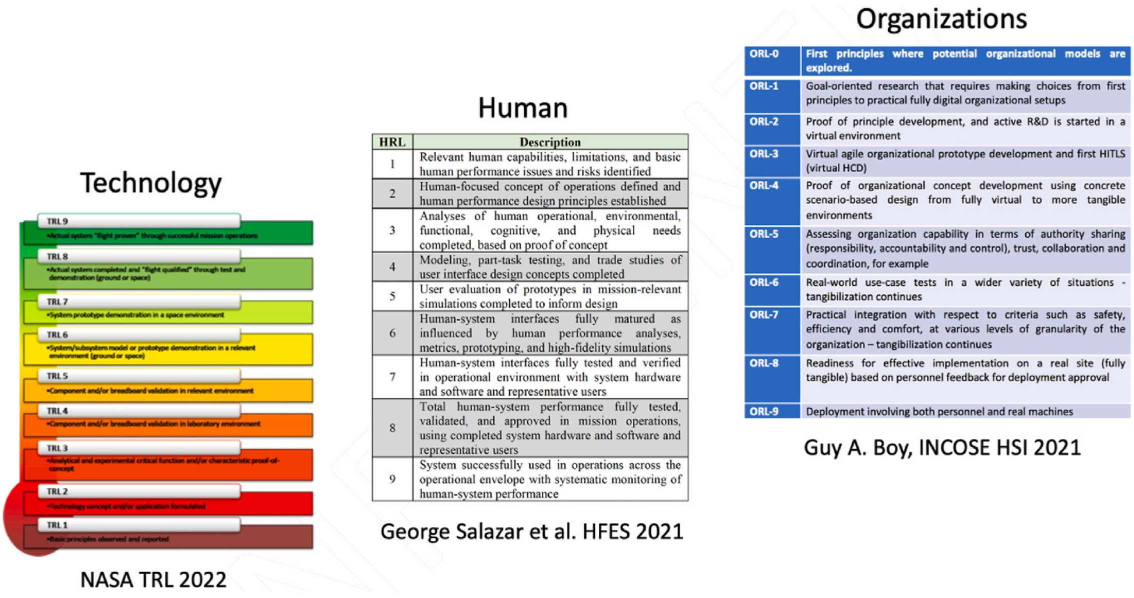
The acceleration of our human-machine societies’ social, economic, commercial, and philosophical transformations shows the need for increased HSI support. Therefore, doing this without a coherent and elaborate HSI ontology would be like an orchestra playing a symphony without music theory. An HSI ontology is currently being developed in a distributed manner (i.e., in various research and development projects) and by doing many progressive syntheses worldwide. Indeed, developing an ontology is a subjective act requiring multiple validations from Subject Matter Experts (SMEs). If practice and project experience show that many SMEs are crucial, a reasonable claim is that three or four SMEs can provide acceptable results. We are not working here on truth but on beliefs and judgments based on experience, often called heuristics. The progressive refinement and validation of such an ontology must occur within a community of practice and determine it. Let’s grow this HSI community where integration and people are taken seriously!

Fig. 18 presents a non-exhaustive HSI ontology that we can extend. Some concepts, such as complexity, sustainability, and digital twin, should be included here. Complexity is inherent to all concepts presented in Fig. 18. Sustainability can be added and will be the subject of another article. Let us state that the digital twin concept is fully included in this ontological graph, which can be considered valid both for a real system and a virtual system (i.e., a digital twin of the real system). When we want to compare a digital twin to the real system it mimics, two ontological graphs are designed and compared.

Such an ontological graph cannot be limited to using a priori knowledge from expert analyses; it is a dynamic tool that must be transformed throughout the life cycle of a system based on operational experience feedback. Therefore, flexibility is required. Not only could concepts be added, but some concepts could be modified, links transformed, and clusters of nodes entirely modified. Moreover, once we start defining and refining such an ontological graph based on gradually acquired expertise and experience, the resulting knowledge must be assimilated and accommodated according to context. This work cannot be occasional. It is repetitive, requiring solid skills acquired gradually.

Of course, the HSI ontology proposed here requires further justification. Several projects are underway on this basis, using proposed axioms, theoretical abstractions, and practical models that we try to validate based on empiricist experiments and three types of maturity metrics (Fig. 19): *Technology Readiness Levels* (TRLs) developed initially and widely used by NASA [102]; *Human Readiness Levels* (HRLs) still under development [103,104,105]; and *Organizational Readiness Levels* (ORLs) that have been proposed more recently [106].

Combining these three sets of readiness levels for the overall HSI assessment is particularly important from the perspective of human-machine teaming, where machines are increasingly equipped with



Technology

TRL 9
•Actual system "flight proven" through successful mission operations
TRL 8
•Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 7
•System prototype demonstration in a space environment
TRL 6
•System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 5
•Component and/or breadboard validation in relevant environment
TRL 4
•Component and/or breadboard validation in laboratory environment
TRL 3
•Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 2
•Technology concept and/or application formulated
TRL 1
•Basic principles observed and reported

NASA TRL 2022

Human

HRL	Description
1	Relevant human capabilities, limitations, and basic human performance issues and risks identified
2	Human-focused concept of operations defined and human performance design principles established
3	Analyses of human operational, environmental, functional, cognitive, and physical needs completed, based on proof of concept
4	Modeling, part-task testing, and trade studies of user interface design concepts completed
5	User evaluation of prototypes in mission-relevant simulations completed to inform design
6	Human-system interfaces fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations
7	Human-system interfaces fully tested and verified in operational environment with system hardware and software and representative users
8	Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users
9	System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

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Organizations

ORL-0	**First principles where potential organizational models are explored.**
ORL-1	Goal-oriented research that requires making choices from first principles to practical fully digital organizational setups
ORL-2	Proof of principle development, and active R&D is started in a virtual environment
ORL-3	Virtual agile organizational prototype development and first HITLS (virtual HCD)
ORL-4	Proof of organizational concept development using concrete scenario-based design from fully virtual to more tangible environments
ORL-5	Assessing organization capability in terms of authority sharing (responsibility, accountability and control), trust, collaboration and coordination, for example
ORL-6	Real-world use-case tests in a wider variety of situations - tangibilization continues
ORL-7	Practical integration with respect to criteria such as safety, efficiency and comfort, at various levels of granularity of the organization – tangibilization continues
ORL-8	Readiness for effective implementation on a real site (fully tangible) based on personnel feedback for deployment approval
ORL-9	Deployment involving both personnel and real machines

Guy A. Boy, INCOSE HSI 2021

Fig. 19. Technology, human, and organizational readiness levels.

artificial intelligence.

Finally, the initial definition of HSI as a combination of HCD and SE must consider a nature-centered perspective of sociotechnical evolution, where humans should no longer be the only ones at the center but should include all living species. This perspective should be the topic of another contribution.

8. Conclusion and perspectives

This article presents a set of contemporary HSI concepts, methods, and tools, that directly consider technology, organizations, and people in the iterative design of complex sociotechnical systems, from design to dismantling. This contribution is the result of the integration of three primary sources: (1) more than forty years of experience in human-centered design and cognitive engineering; (2) a compilation of various research contributions in the HSI field; and (3) incremental work on generic HSI models and knowledge representations in several research and application development efforts within our research program, covering a range of previously-cited use cases across various industry sectors, such as future air combat, telerobotic oil and gas management, remote maintenance, increasingly autonomous train systems, and healthcare.

HSI is about dynamically building systems that meet human and organizational requirements, while gradually, and with agility, refining needed emergent human skills and appropriate organizational structures. As this article shows, these requirements will likely evolve during the life cycle of a socio-technical system. Discovering emergent behaviors and properties requires testing for tangibility and, therefore, also requires critical principles and metrics. These can be broken down into five factors leading to five design and management processes [72]: complexity; maturity in terms of TRLs, HRLs, and ORLs; flexibility; stability and resilience in a wide variety of situations; and sustainability (i.e., thinking ahead in terms of possible futures).

Taking all this into consideration, we must use digital engineering wisely. Specifically, digital HITLS systems using virtual prototypes enable the discovery of emergent behaviors and properties that need to be used to improve the incremental development of sociotechnical systems. For this reason, scenario-based design combined with HITLS allows observing and analyzing human activity at depth. Moreover, the design of increasingly autonomous machines requires more profound studies of operational performance, trust, and specifically human-machine collaboration. Indeed, this epistemological approach to HSI and the resulting ontology are essential to help better articulate and understand how we will live in this upcoming Society 5.0 with AI components. Another consideration is Digital Human Modeling (DHM) [107] as part of HSI, but that should be explored in another paper (i.e., should we consider real people in the loop during the design process of a sociotechnical system or digital models of people might suffice?).

Finally, as a transdisciplinary field, HSI should include more circular economy models, social and political sciences, crowdsourcing, and social innovation, which is a limitation of our current work – we cannot do everything at once! We are aware of this and plan to expand our epistemological account soon. However, hopefully, this article will encourage further research and development on this challenging epistemological enterprise that attempts to improve the clarity, consistency, flexibility, meaning, effectiveness, usefulness, and usability of HSI philosophies, concepts, methods, and tools.

Declaration of competing interest

There is no conflict of interest on the article, title:
An Epistemological Approach to Human Systems Integration.

Data availability

No data was used for the research described in the article.

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