Human-Systems Integration

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Definition/Abstract

Human-systems integration (HSI) denotes a possible evolution of two disciplines, that are Human Factors and Ergonomics (HFE) and Human-Computer Interaction (HCI) that led to Human-Centered Design (HCD), more specifically within the field of Systems Engineering (SE). HSI pragmatically considers the TOP Model that supports integration of Technology, Organizations and People during the whole life cycle of a system. HSI is inherently multi-agent, takes the system approach, and looks for the elicitation of emergent systemic properties through human-in-the-loop simulations (Virtual HCD). Human and machine are represented as systems defined by their structures and functions, which are characterized using the "context-resource orthogonality" framework. This encyclopedia entry provides HSI psychological and sociotechnical foundations, based on a non-linear and self-organizing system perspective that departs from the traditional linear reductionist approach in psychology and engineering. This HSI epistemological endeavor addresses concepts such as separability, familiarity, emergence, tangibility, agonist-antagonist processes, symbiotic cognitive and physical structures and functions.

Keywords: human-systems integration, tangibility, human-centered design, system science, systems engineering, systems of systems, complexity, open-nonlinear self-organizing systems, emergent properties, human-in-the-loop simulation, multi-agent modeling, TOP model.

1. Introduction

The main objectives of this encyclopedia entry are (1) to improve our understanding of why psychologists and social scientists together with systems engineers and other stakeholders involved in the design of complex systems should be working in a participatory manner, (2) to provide salient elements of the emergent Human Systems Integration (HSI) field, and (3) to consider how new complex systems impact our working and everyday lives. But first, let us provide why HSI has become so important today, and opens the possibility of a new transdisciplinary endeavor in both science and engineering.

It is common to observe that technological systems are often integrated too late, leading to both wrong or unexpected usages, and lack of resilience facing unexpected events. Resilience engineering has been studied (Hollnagel, Woods, & Leveson, 2006), but without providing solid fundamental engineering design solutions. A large amount of money is still spent to improve usages by developing appropriate user interfaces and operations procedures. This is the logical result of technology-centered Systems Engineering (SE) of the 20th century. What did happen? Engineers had to design and develop machines mostly using mechanical engineering, making tangible things from tangible things (i.e., from pieces of metal that were assembled, screwed and so on). During the last three decades of the 20th century, electronics and software were massively incorporated into mechanical machines to improve their functionalities and usability. Automation (automatic control) and Human-Computer Interaction (HCI) were the main disciplines that were used to this end. This move could be summarized as the **hardware-to-software shift**.

Let’s take an example. During the seventies, car engines could be mechanically maintained more of less easily by car owners. Today, once a failure occurs, car owners let car maintenance professionals provide a diagnostic using a software-based system that provides meaningful information, such as the price it will cost to fully repair failure’s cause. This shift increases system’s availability by minimizing time it will take to repair the car. System’s components have become standardized, easily changeable and disposable.

Since the beginning of the 21st century, almost all technological systems are designed on computers. First concepts are presented on PowerPoint slides. Then, more sophisticated models are produced using appropriate Computer-Aided Design (CAD) tools. These models are subsequently used into simulations, which are with human(s) in the loop. More specifically, Human-In-The-Loop Simulation (HITLS) provides means for discovering potential emerging behaviors and properties that cannot be anticipated without observing activity of the various human and machine agents. By enabling incremental discovery of emergent behaviors and properties (Boy, 2013), HITLS is a key resource for Human-Centered Design (HCD), which cannot be done without an agile development approach (Schwaber, 1997; Schwaber, 2004; Sutherland, 2014). In fact, HITLS makes HSI possible and effective. This is great news! However, since such virtual HCD relies on the use of virtual prototypes, now often called digital twins, tangibility is at stake and needs to be considered seriously. Indeed, a virtual prototype of an aircraft is not a real aircraft! The virtual prototype has to be transformed into a physical prototype. This move could be summarized as the **software-to-hardware shift**.

Let's take an example. Aircraft wings are digitally designed using CAD and fluid dynamics software, providing requirements for the development of wings, which can be 3D printed to produce physical wings. Most importantly today, tangibility of emerging Artificial Intelligence (AI) algorithms (also called data science) used in design and operations of complex systems must be studied in depth. The concept of digital twin is crucial in HITLS. Many instances of digital twins are currently available, more specifically in the form of aircraft simulator (Figure 1).

Let's emphasize the need for HSI, where a system can be both a human and/or a machine. It provides epistemological foundations for the psychology of HSI, articulated around concepts such as separability, familiarity, emergence, tangibility, agonist-antagonist processes, symbiotic cognitive and physical structures and functions, and most importantly a non-linear and self-organizing system perspective that departs from the traditional linear reductionist approach in both psychology and engineering. Tangibility assessment still requires combining creativity and experience, as well as complexity, flexibility, stability, maturity and sustainability metrics.

Figure 1. Example of a tangible combat aircraft simulator.

2. Human System Integration: A historical approach

It would be difficult to make sense of HSI without defining the distinction between **task** and **activity**. A task is what is prescribed to be done. An activity is what is effectively done once the task is executed. Task analysis has been extensively used to support the design of user interfaces (Kirwan & Ainsworth, 1992; Mori, Paterno & Santoro, 2002; Diaper & Stanton, 2004). However, usability studies have shown that activity observation and subsequent analysis are crucial to improve interaction design (Kaptelinin & Nardi, 2006) and ergonomics (Leplat, 2008). For a long time, the main problem was that activity was only observable on existing systems whether currently used systems prior to novel design or once a new system was fully developed. On the one hand, activity analysis on existing systems prior to starting engineering design usually forces conservatism and continuity; disruptive innovation can be considered as dangerous. On the other hand, activity analysis once a new system is fully developed is likely to show design flaws that will or will not be possible to fix in depth from a systemic point of view; only cosmetic patches can be brought at the user interface level. This has been done for a long time.

Historically speaking (Figure 2), the field of Human Factors and Ergonomics (HFE) was born after World War 2. Ergonomists are mainly psychologists and physiologists. During the early eighties when micro-computers started to be adopted by a large public and more specifically text processing was starting to become current practice, ergonomists got interested in the way people interacted with computers. Human-Computer Interaction (HCI) was born, introducing new kinds of investigations where computer scientists had to deal with human factors in computing systems (Card et al., 1983). HCI specialists took the lead on the design of Graphical User Interfaces (GUIs). HCI contributed to the development of a large set of task analysis methods, limited however to computing systems and not necessarily to multi-physical complex systems, such as aircrafts, air traffic control systems and nuclear power plants, where observed activity is generally different from related prescribed tasks, typically provided in the form of operations procedures. Related user interfaces, whether they are called cockpits or control rooms, involve deeper considerations than what generic desktop GUIs usually bring. Unfortunately, many user interfaces tend to hide engineering design flaws, and unfortunately adapt people to developed systems, creating situation awareness problems in critical situations.

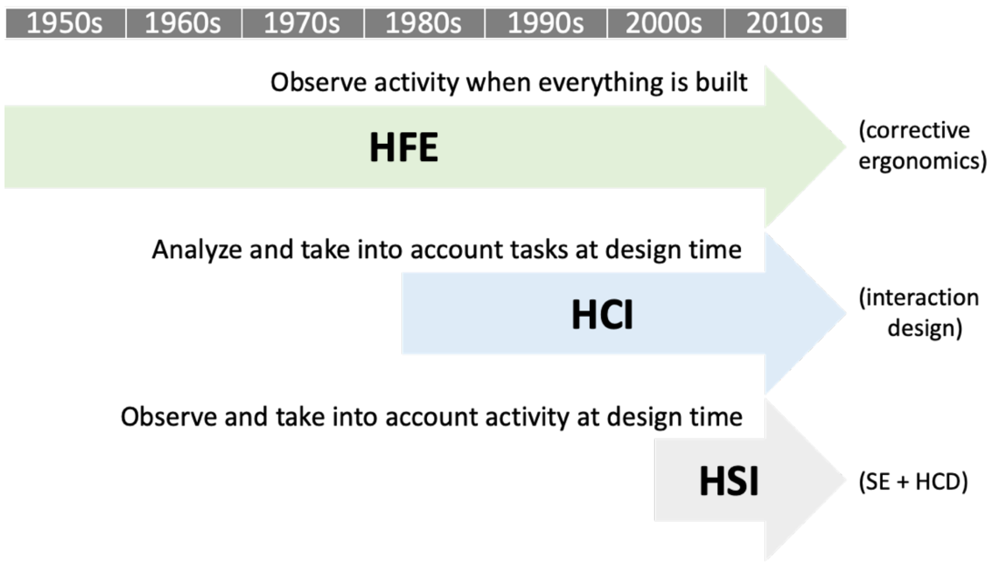

Figure 2. Evolution of human-centered technology approaches.

Since the beginning of the 21st century, SE started to become aware of the importance of human factors in engineering design. HSI of sociotechnical systems was born as a combination of HCD and SE. More specifically, HSI is intrinsically model-based, and concurrently considers

Technology, Organizations and People (TOP) during the whole life cycle of a system (Figure 3). This is the reason why the modeling framework shifted from single agent to multi-agent.

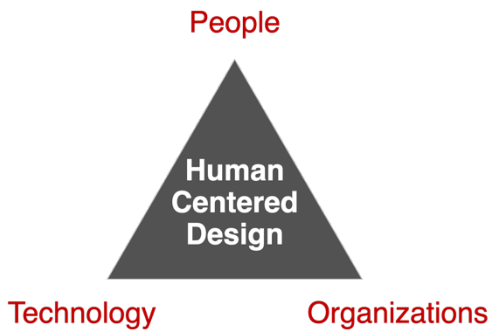

Figure 3. The TOP model for Human-Centered Design.

HSI requires a more formal definition of what a “system” is about. But before providing a definition, it is important to state that HSI opens the way to a new multi-agent approach, in contrast with the single-agent approach provided by human information processing models (Newell & Simon, 1971; Rasmussen, 1986), to psychosociology, introducing an alternative to traditional linear approaches considering cognition and socio-cognition as sequential information processing. HSI considers from the outset that the systems are open, non-linear and self-organized in the sense of the theories proposed by Tableb on the one hand and Klochko on the other (Taleb, 2007; Klochko, 2007). Taleb proposed this new definition of systems from an extrinsic point of view (i.e., our environment can be considered as an open nonlinear and self-organized system). Klochko proposed an intrinsic point of view (i.e., our cognition can be considered as an open nonlinear and self-organized system). Klochko’s proposal follows stages of child's development proposed by Piaget (1936), and the selective property of our mind proposed by Vygotsky (Vygotsky & Luria, 1993). Our brain is able to process gigantic amount of information, not by processing it all, but by selecting relevant parts that make sense to us. Relevance is about meaning. We can talk about meaningful reality, and not about objectively sensed reality.

3. What does the term "system" mean?

A system is a **declarative representation** of either a natural or an artificial entity. Natural entities can be human beings (e.g., human beings are open nonlinear systems in Klochko's sense), organs of a human being (e.g., physicians talk about neurological system or cardiovascular system), plants and animals or organizations of them (e.g., the reproduction system of flowers by pollination associating bees; flocks of birds). An artificial entity can be an abstraction (e.g., an idea, a law, a method), an object (e.g., a chair) or a machine (e.g., a car, a washing machine) that was built by a human being to facilitate and support the execution of specific tasks. A system has at least a structure and a function (Figure 4). It can be either cognitive (or conceptual), physical or both (Boy, 2017). Today, machines have cognitive functions (e.g., the cruise control function on a car enables the car to keep a set speed) and cognitive structures (e.g., interconnectivity within systems of subsystems such as an industrial company). Note that a human can include a machine (e.g., a human may have a pacemaker machine), and a machine can include a human (e.g., an aircraft includes pilots and passengers).

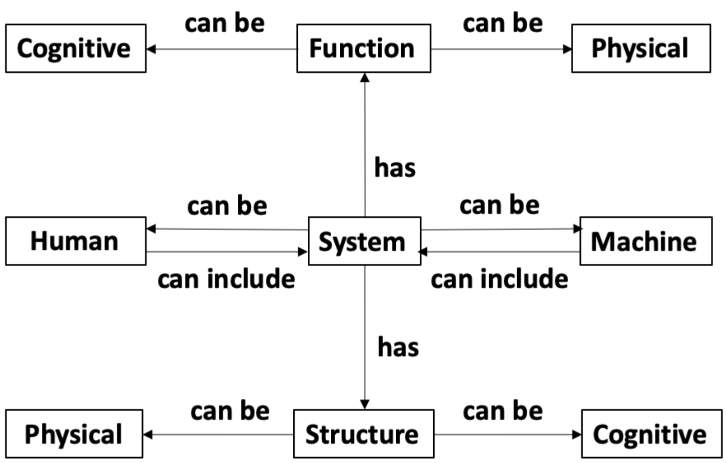

Figure 4. The cognitive-physical structure-function representation of a system.

In addition, the conventional single-agent definition of a system function as something that transforms an input into an output should be extended to a multi-agent perspective. In the teleological multi-agent sense, a system function is defined by three attributes:

- a role;
- a context of validity;
- a set of possible and necessary resources.

At this point, it should be noted that the concept of "system" commonly used in systems engineering is very similar to the concept of "agent" in artificial intelligence and cognitive science. For example, a postman is an agent of an agency that is commonly called "The Post". The post can be represented by system of systems, where the postman is a system. A typical postman's function can still be defined as having a (prescribed) task of "delivering letters" (i.e., function input). His/her activity (i.e., function output) may not always reflect such a prescribed task because the context may change, either his/her capacity may intrinsically change (e.g., the postman is tired or sick), or environmental factors may extrinsically change (e.g., heavy rain or excessive traffic).

Context of validity of postman's role (i.e., delivering letters) can be defined by a time context (e.g., from 8:00 am to noon, and from 2:00 pm to 5:00 pm) and a space context (e.g., the neighborhood where he/she has to deliver letters). Context can be normal (i.e., the same job every day) or abnormal (e.g., some other postmen are not available and the postman in duty needs to expand his/her time and/or space context). Postman's resources can be physical (e.g., a bag and a bicycle) or cognitive (e.g., a pattern-matching cognitive function that enables him/her to put each letter in the right mailbox, matching the name of the street, the number of the house and the name of the addressee). At this point, it becomes clear that a function is a function of functions (e.g., "delivering letters" is a function of another function, the "pattern-matching" function). More generically, function's resources are systems, which can be either physical, cognitive or both. This representation is very convenient for function allocation in a SoS (i.e., among systems [or structures] in a network of systems).

4. Various types of situations for context management

The term "situation" is commonly used to denote something that happens, such as an event, a state of affairs of someone, a location or a process at a particular time, or a context that specifies a set of persistent conditions. A situation can be a generic pattern, or an episodic set of conditions. Summarizing, we will consider that a situation is defined by a set of states, in the common sense of control theory. More formally, a situation S may refer to a dynamic set of states (i.e., a situation varies in time), $S(t) = \{s_i(t); i=1,n\}$, including multiple derivatives, in the mathematical sense, such as velocity and acceleration (i.e., a situation is not only a static description, but also an evolution).

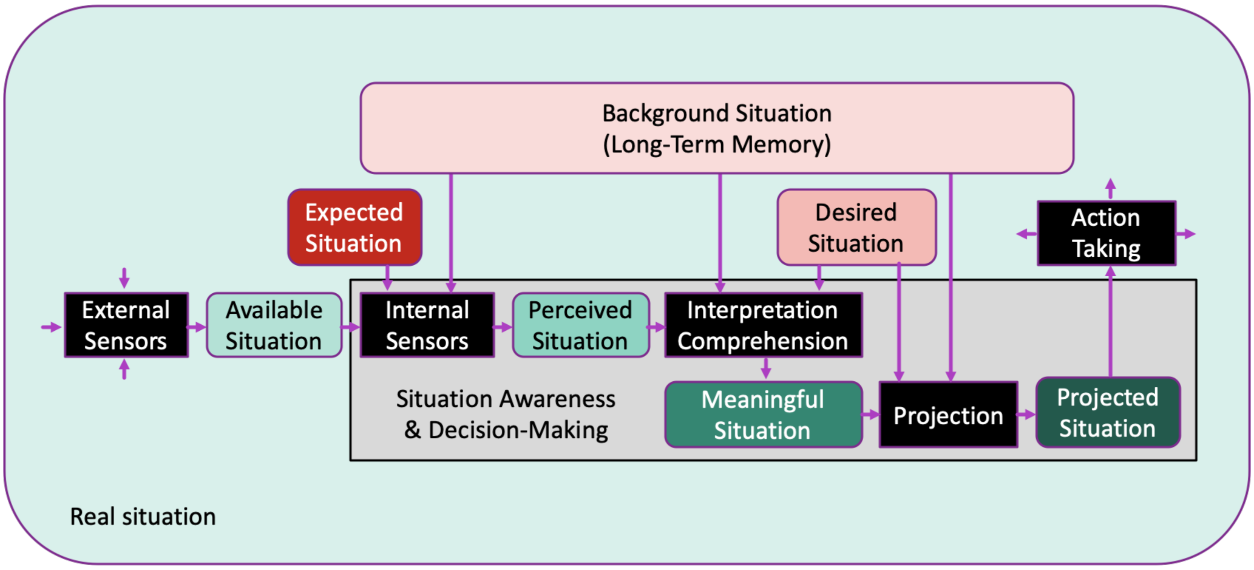

Figure 5. Various interconnected human-centered meanings of the situation concept.

Following what Mica Endsley already described in her situation awareness model, the perceived situation also needs to be understood at a conscious level (Endsley, 1995ab, 1998; Endsley & Garland, 2000; Boy, 2015). The concept of situation has several interrelated facets (Figure 5): the "real situation" is characterized by an infinite number of highly interconnected states; the "available situation" is characterized by a set of states available to a human observer through external sensors; the "perceived situation" is a subset of states of the "available situation," directed, augmented and/or transformed by what is being expected (i.e., the "expected situation") and the long-term memory of the agent (i.e., the "background situation"); the "expected situation" supports event-driven behavior (i.e., what we anticipate); the "meaningful situation" is a subset of the "perceived situation" augmented by the "desired situation" (i.e., what we want to do) and the background situation (i.e., directed by experience and habits); we can talk about an interpretation process at this point; the "desired" situation expresses a goal-driven behavior (e.g., what we want to get from what are doing in the current situation); the "projected situation" can then be considered as a subset of the meaningful situation augmented by the background situation (e.g., experience and habits).

5. Systems as resources: the multi-agent paradigm shift

For a long time, engineering schools taught linear algebra as a major mathematical package for future engineers. Very little attention has been brought to non-linear models and complexity science. Consequently, engineers tend to think linearly. In addition, human and social sciences tend to adopt most popular mathematical models for data analysis, mostly in statistics (e.g., linear regression). It is not surprising that both worlds (i.e., engineering and human factors) have difficulties when non-linearities occur in the course of industrial or life-critical operations (Boy, to appear). The Taleb's Black Swan metaphor is interesting to consider here because it encapsulates the concept of human antifragility that involves signals for homeostatic processes that fight to keep the overall system safe and working (Taleb, 2007[1]). In other words, in everyday practice, moving from linear to non-linear consists in moving from procedure following, to cooperation with machine automation to problem solving (Figure 6).

Many complex systems and complex situations cannot be reduced to simple linear systems or situations, we need to get familiar with them in order to understand them and adapt to them. The opposite concept of complexity is not only simplicity, it is also familiarity. For example, when you move from one location to another for living, you are likely to find the new location very complex to navigate in it, but after a few months, you become familiar with it, locating the bakery next to the shoemaker, and so on. The more familiar you become with the new location, the more you find it simple to navigate in it. What really happens relies on the network of shops, streets, roads and

[1] A second edition, published in 2010, provided a new section on robustness and fragility; ISBN 978-081297381.

houses and their interrelations (i.e., their systemic structures and functions). When you have become familiar with nodes and links of this network, everything becomes so simple! Therefore, instead of avoiding complexity by reducing it to linear models, it is crucial to learn about this complexity (i.e., become familiar with it).

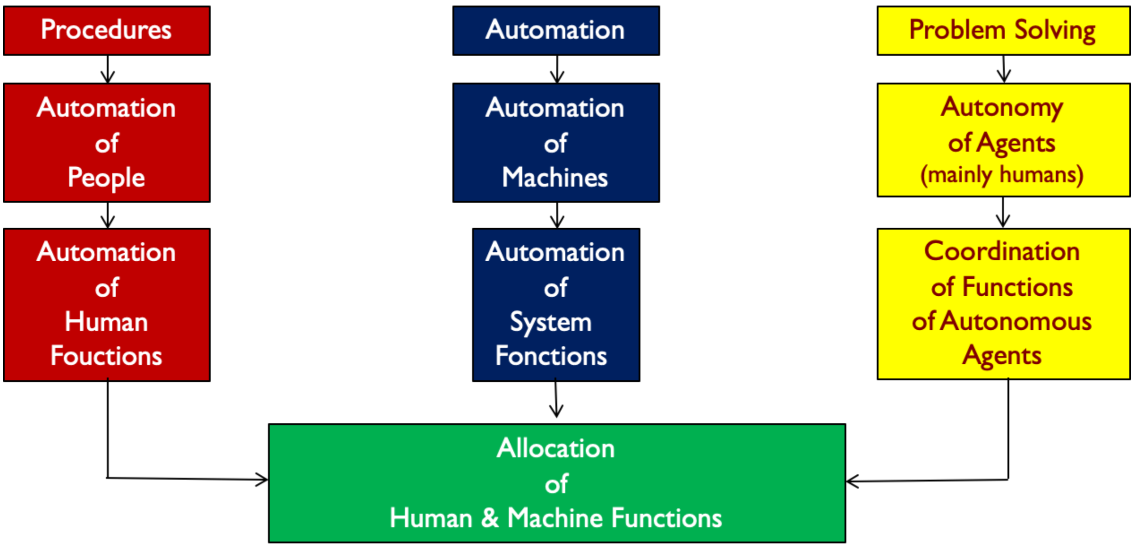

Figure 6. Procedures, automation and problem solving
leading to the allocation of human and machine functions (Boy, 2020).

In many situations (i.e., normal, abnormal and emergency), human operators of life-critical systems typically follow procedures and/or use machine automation. However, outside of such procedures and automation definition contexts, human operators have to directly solve problems. In these cases, they need to have enough autonomy to handle current situations correctly.

What do we mean by autonomy? Being autonomous requires knowledge, experience and sometimes boldness. When these requirements are not present, human operators have to get external assistance. This is where the multi-agent approach enters into play. An autonomous system is necessarily a multi-agent system, because it is equipped with the necessary agents that are capable of following appropriate procedures, using automated tools, and solving problems at hands, either intrinsically (e.g., a mountaineer who learned and trained enough to have necessary knowledge and skills to climb a difficult peak) or extrinsically (e.g., a team of aerospace engineers and astronauts that has all necessary knowledge and skills to solve a problem in a spacecraft such as in Apollo 13 successful accident). An excellent illustration is the experience of Apollo 11, when Neil Armstrong landed on the Moon (Mindell, 2008). An intrinsic multi-agent system is not equivalent to a single-agent system because it is equipped with a “team” of sub-systems working together (e.g., functions working not only in sequence as a classical information processor, but also in parallel, cooperatively and/or competitively). An extrinsic multi-agent system is what we usually call a multi-agent system for short.

The distinction between automation to autonomy deserves to be better understood. Automation is about defining, developing and using procedures defined in a specific context. Automation deals with a close, linearized and rigid world. It is usually thought as a single-agent system. Autonomy is about incremental learning of experience in multiple contexts and handling expected as well as unexpected situations using intrinsic knowledge and skills and dedicated extrinsic support. Autonomy deals with an open, non-linear and flexible world. Consequently, it is about trust, collaboration and self-organization. It is typically thought as a multi-agent system.

A first solution is to consider models the systemic interaction models (Boy, 2020): supervision; mediation and cooperation. Considering these three systemic interaction models, combined with procedure following, cooperation with automation and problem solving (Figure 9) contributes to a useful multi-dimensional multi-agent model that should also consider that agents can be working together toward a same goal or the opposite. We are facing an epistemological question of defining how multi-agent systems work. A specific answer to this issue was provided in system science by Bernard-Weil who proposed the agonistic-antagonistic paradigm that combines cooperation and competition of two groups of agents (Bernard-Weil, 2003). Bernard-Weil studied the dynamics of agonistic-antagonistic bio-medical networks to better understand emerging phenomena, and types of control when unbalances between the two groups of agents occur. Further work should be devoted to this fundamental question. In the meantime, let us concentrate on a method that enables the elicitation of knowledge useful for giving life to such multi-agent systems.

6. Associating procedural and declarative knowledge: the PRODEC method

The association of the situational framework defined in Section 4 together with the system declarative representation provided in Section 5 leads to what is denoted "context-resource orthogonality" (i.e., the articulation of procedural and declarative knowledge). Procedural knowledge is about timeline of events and actions (e.g., stories, episodes, scripts, procedural scenarios), and describes meaningful situations. Declarative knowledge is about multi-agent organizational structure-function models and describes resources as systems. Procedural and declarative knowledge respectively denotes what is functionally and structurally possible.

Cognitive psychology and computer science cross-fertilized each other for a long time. Indeed, procedural knowledge and its distinction with declarative (or conceptual) knowledge has been developed in several fields related to cognition such as educational science (McCormick, 1997) and development psychology (Schneider, Rittle-Johnson & Star, 2011), including mathematics education (Star, 2005; Hiebert & Lefevre, 1986; Carpenter, 1986), user modeling (Corbett & Anderson, 1994), an experimental psychology (Willingham, Nissen & Bullemer, 1989; Lewicki, Czyzewska & Hoffman, 1987; Richard, 1983).

The theater metaphor helps figuring out what the PRODEC method is about (Boy et al., 2020). First, a writer produces an essay that tells a story, available in a procedural manner. Then, a director selects, in a declarative manner, actors who have to read the essay and learn their roles and scripts procedurally and coordinates them. PRODEC has been designed to be used in HCD to benefit from both operations experience (i.e., human operators will be asked to provide their salient operations stories) and definition of objects and agents involved in the targeted human-machine system to be designed (i.e., the design team will provide prototypes at various progressive levels of maturity). PRODEC consists in using the following procedure:

1. Elicit and review all tasks involved in the achievement of various goals;
2. Describe them as procedural scenarios;

3. Elicit cognitive (and physical) functions in the form of role (associated to tasks and goals), context and associated resources (declarative scenarios);
4. Describe and refine elicited resources in terms of structures and functions (using the formalism presented in Figure 4);
5. Iterate until a satisfactory solution is found.

Procedural knowledge is elicited from subject matter experts in the form of chronological scenarios, together with system-of-systems performance criteria for the assessment of accuracy, impact and probability of collaboration and trust, for example. System performance relies on the articulation of three factors encapsulated within the *AUTOS Pyramid*[2] (Boy, 2011).

Tangibilization deals with system's physical and figurative (or cognitive) tangibility assessments (i.e., the fact that we can grasp a system physically and figuratively). Figurative tangibility is about meaningfulness. Domain ontology, or system ontology, can be divided into functional ontology and structural ontology.

7. Conclusion

This entry of the Palgrave Encyclopedia of the Possible proposes a fundamental approach to human-systems integration (HSI) from a psychology and social sciences perspective, associated to useful concepts, methods and tools for its development. HSI deliberately takes a long-term perspective, where possible futures are anticipated and tested from the very beginning of the life cycle of a sociotechnical system. HSI contrasts with the traditional engineering approach that necessarily considers causal prediction of short-term futures. HSI is both a process and a product, which should take place as early as possible during the design process and evolve during the overall life cycle of the product. Being able to observe activity at design time is a brand-new

[2] Artifact, User, Task, Organization and Situation.

capability in engineering design, because modeling and virtual prototyping means are now available and realistic enough to support human-in-the-loop simulations.

Human-centered design combined with agile systems-of-systems engineering approaches, effectively supports HSI. Indeed, technology, organizations and people must be considered concurrently during the whole life cycle of a system in which functions can be incrementally allocated to more appropriate agents with respect to appropriate principles and criteria. This means that HSI is no longer a matter of adapting people to machines by crafting, often too late, user interfaces and operations procedures, but an integrated approach based on the system-of-systems concept that integrates people and machines into articulated sociotechnical systems. In fact, HSI theory is far from being fully developed, and requires more formal investigations and heuristic experimentations. More specifically, HSI dictates that improving autonomous complex systems, requires improving autonomy for all stakeholders, including people and machines.

HSI requires more investigations based on complexity science and system science, where concepts and issues, such as emergence, separability and complexity familiarity, should be further explored. Finally, HSI developed using digital twins should be based on strong tangibility principles, scenarios and assessment criteria, properly defined along five directions: complexity, maturity, flexibility, stability and sustainability. Number and content of these dimensions will be probably extended with respect to ongoing engineering design, research and innovation developments.

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Cross-referenced terms from the encyclopedia

Anticipation; consciousness; creativity; heuristics; reality; simulation; virtual reality; Vygotsky.

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