FROM REQUIREMENTS TO PROTOTYPING: APPLICATION OF HUMAN-SYSTEM INTEGRATION METHODOLOGY TO DIGITAL TWIN DESIGN

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ABSTRACT

Industrial digital transformation is bringing a need for new tools and concepts. However, designing such complex tools and concept requires methods to be correctly implemented. These methods are studied as part of system engineering to satisfy various identified goals, and more specifically human-system integration, which is the topic of this paper. This article introduces the method used to define key elements of human perception of reality called reality anchors to design scenarios to be tested in a digital twin prototype. This method goes from regulation study to user cognitive function analysis on the specific case of digital twin designing in oil-and-gas industry. This method highlighted the differences between theoretical process and the followed process as well as tools and competencies used to identify reality anchors. This knowledge will then be used to implement a new process to be implemented with a digital twin and scenarios to test the prototype using realistic simulation.

Keywords: Digital twins, Design methodology, User centred design, Process modelling, Oil-and-gas domain

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1 INTRODUCTION

The digital transformations introduced by 4.0 industrial revolution have transformed industries into complex systems (Satoglu et al. 2018). A complex system is defined as "a large network of components, many-to-many communication channels, and sophisticated information processing that makes prediction of system states difficult" (Grieves and Vickers 2017).
In this transformation, the digital twin (DT) (Grieves 2012) emerges as a solution for humans to manage complex systems. A DT is defined as a dynamic representation of a physical system using interconnected data (Camara Dit Pinto et al. 2021) making it a complex system in itself. DTs are used in multiples industries (e.g., aeronautic, manufacturing, etc.) to represent and interact with a real system (Negri, Fumagalli, and Macchi 2017).
Designing such complex system to help the user deal with complexity requires user-centered methodologies, which involve human-in-the-loop tests with users during the design phase. However, complex systems are difficult to reduce to models to design a realistic prototype for testing. As the DT is a representation of a real system with which the user interacts, we propose to focus on understanding the links between the user and the real system for which a DT is designed. These links are tangibilized through the concept of reality anchors.

This article presents the methodology used to elicit user's reality anchors from the managed system. This methodology allows to define realistic scenarios for human-in-the-loop tests. It is applied to the design of the DT of an oil-and-gas facility within the TOTAL company1 which will be used in control room as a tool for managing the facility in normal and downgraded situation.
Section 2 introduce the notion of complex system and its implications within the system engineering and, in particular, in the human-system integration paradigm. Section 3 presents the industrial case study in more details. Section 4 presents the three-step methodology based on regulation studies, interviews with expert of the domain, and cognitive function analysis. Section 5 is devoted to a discussion of the results of the methodology and future developments.

2 COMPLEX SYSTEMS

The field of system engineering is concerned with the development and elaboration of methodologies to improve the design of systems. A simple system with few components can be understood by users when they interact with it but that is no longer the case complexity of the system increases. Human-centered design methodologies address the design of complex systems for and with users. In this section we define the DT as a complex system intended to be used by humans and we establish the need for contribution from the fields of system engineering, Human Centered Design (HCD) and Human System Integration (HSI) fields.

2.1 The digital twin as a complex system

DT is defined, in our context, as a dynamic representation of a physical system using interconnected data, models and processes to enable access to knowledge from past, present and future states in order to manage action upon this system (Camara Dit Pinto et al. 2021).
DTs are classified according to four levels of maturity (Madni, Madni, and Lucero 2019):

- A First level DT is a virtual prototype that is mainly found in PLM tools. These pre-DTs are used to support decision making during the design phase.
- A second level DT is a virtual representation of a real system with the ability to collect information about the physical system using sensors. These DTs are used to monitor performance, health, and maintenance data to support decision making throughout the system life cycle.
- A third level DT uses real time updates and machine learning algorithms to adapt the interface to user preferences.
- A fourth level DT uses high-level abilities to take into account the system environment and extract knowledge for the physical twin monitoring.

The purpose of any-level DT is to enable the human user to manage a physical system. Considering the human into its design is therefore necessary. This can be achieved by making the DT evolve

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through the maturity levels during its design and implementation. Starting by designing the DT representing a simulation and implementing up to the fourth level environment and knowledge abilities. Defining such design methodology can be considered as part of the system engineering field.

2.2 Systems engineering of complex systems

System engineering (SE) is a discipline that focuses on engineering techniques and methods for system design. It started in 1950 with a teaching attempt at the Massachusetts Institute of Technology to formalize tools and methods for designing complex systems (Gorod, Sauser, and Boardman 2008). SE constantly evolve to develop theoretical guideline, referenced as “best practices”, for the engineering of systems (Sheard and Mostashari 2009). These enable to define a standard goal-oriented engineering process composed of (1) functional specification definition, (2) design, (3) testing and validation and (4) manufacturing (Minai, Braha, and Bar-Yam 2006.).

However, in the face of increasingly complex systems and systems of systems, SE has evolved to define a complex system of system engineering paradigm with a focus on systems adaptability (Gorod et al. 2008). As a result and as part of one of the SE multiple goal-oriented process, human-system integration has appeared using human-centered design principles.

2.3 Human centered design and human system integration

In traditional technology-centered engineering, as the complexity of systems increases, the role of human agent is often barely considered in the design process. Design is usually thought from the inside out and therefore leads to the definition and implementation of user interfaces to bridge the gap between users and the system. Instead of enabling people they force them to adapt to the machines. The increasing complexity of systems has brought these "patches" to their limits. Conversely, human centered design (HCD) contributes to consider end-users as early as possible (Boy 2013). These methods have been defined to involve users in the system designing phase and adapt systems to users (Maguire 2001).

HCD is now used in a large variety of domains, among which Human Computer Interaction (HCI) is the figurehead. In this field, understanding user’s needs is essential and HCD is the widely implemented (Anderson, Norman, and Draper 1988). This is the main reason HCI methods and tools have been chosen to support our current approach to DT design.

The Human System Integration (HSI) paradigm appeared from the combination of both SE and HCD as a unifying concept (Boy and Narkevicius 2014). It is currently further defined within the HSI working group of INCOSE (International Council on Systems Engineering2).

HSI is the approach considered in this study to fully involve the human during the entire system engineering process.

3 CASE STUDY

The methodology presented in this paper is developed around a case study from the Exploration and Production (EP) branch of the oil-and-gas company TOTAL. The development of DT is explored as a solution for the remote management of EP facilities in order to limit operator exposition to operation hazards.

3.1 Industrial context

Control room (CR) operators continuously monitor EP facilities to ensure performance, process continuity and appropriate responses to downgraded situations. Downgraded situations are defined as any abnormal situation, in which a facility is operating outside its context of definition, resulting in an increase in operational risk. CR operators have access to multiple tools that facilitate access to information regarding process health management, human movement, and alarms. CR operators also ease communication among field operators, management staff and technical experts. This information is used to make decision during downgraded situations. The process of acquiring situational awareness is part of the decision-making process (Endsley, Bolte, and Jones 2003) and consists of three levels, (1) perception of elements that make up the situation, (2) comprehension of the situation, and (3)

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projection to possible future situations. The perception of elements represents the acquisition of data about the situation. The comprehension represents the modeling of the situation by relating the elements perceived. The projection represents the extrapolation of the situation from the understood situation and previously acquired knowledge. During these processes, memories are used such as the working memory for information processing, the short-term memory for data and information storage, the long-term memory for information and knowledge storage (Endsley 1995). This multi-level storage capability is identified as the one to be supported by the DT (Camara Dit Pinto et al. 2021).

3.2 Digital twins

Regarding this human process, a study of operators' work through a regulation study as well as interviews highlighted the ability for DT to support situation awareness in control rooms (Camara Dit Pinto et al. 2021). This study exposed the composition of DT with eight components all related to the support of situational awareness:

- The real system model for simulation purposes and physical representation (supporting perception and projection),
- The contextual model for the representation of the environment, humans, and equipment (supporting perception),
- The sensors data for the continuous monitoring of the system and updating the models (supporting perception),
- The interface for the transmission of information and knowledge to the user (supporting perception, comprehension, and projection),
- The memory for storing internal or external data (supporting comprehension),
- The data management components for the reduction, selection and processing of data through the DT (supporting perception, comprehension, and projection).

This operational definition of a DT enables it to act as an all-in-one tool for process management with capabilities to manage downgraded situations on oil-and-gas facilities. However, we argue that all these findings can be adapted to any industrial or energy producer context.

4 METHODOLOGY

The HCD paradigm recommends that systems should be developed incrementally and tangibilized into the final product (Boy 2013). Therefore, in the case of a fourth level DT, the choice is made to start the development phase with a simulation of a real system. The HCD paradigm also recommends the use of human-in-the-loop simulations to extract user needs during the design process. To follow this methodology realistic scenarios should be implemented to obtain accurate information from users.
Furthermore, the implementation of a DT, as a new tool in the control room management process, implies changes in this process. Therefore, a methodology inspired by the GIM method (Wehbe, Merlo, and Pilnière 2020) in the specific case of DT implementation was followed. As in the GIM method, the system "as is" is modeled, and analyzed in order to define the system "to be". This methodology is called the Reality Anchor Elicitation Methodology (RAEM).

4.1 General description of the proposed methodology

To enable real world simulation o for prototyping purpose, we propose to identify reality anchors for the CR operator in the as-is process. Indeed, in the control room operators already experience and control the outside world from a remote perspective: through the process management software and radio contacts with ground operators. The REAM focuses on extracting these anchors or link points between reality and the operator with the goal of relying on them in the digital twin.

This methodology is structured as follows (Figure 1):

1. A desk review of company's operating procedures is performed to extract a theoretical process, the required tasks and prescribed tools that are used in the as is process. These are used to guide the interviews with CR operators.
2. These elements are used to conduct interviews with expert user (here CR operators) to refine the actual process, tasks performed, and tools used.
3. Finally, a cognitive function analysis is performed on the process and the task models to identify cognitive resources involved in the activities of the CR operators. The cognitive functions are

defined as the human or machine functions that transforms task into activities (Boy 1998). These are characterized by role, contexts, and resources. The cognitive function analysis performed in this methodology focuses on the definition of reality anchors as cognitive resources that denotes the real world from the operator's perspective.

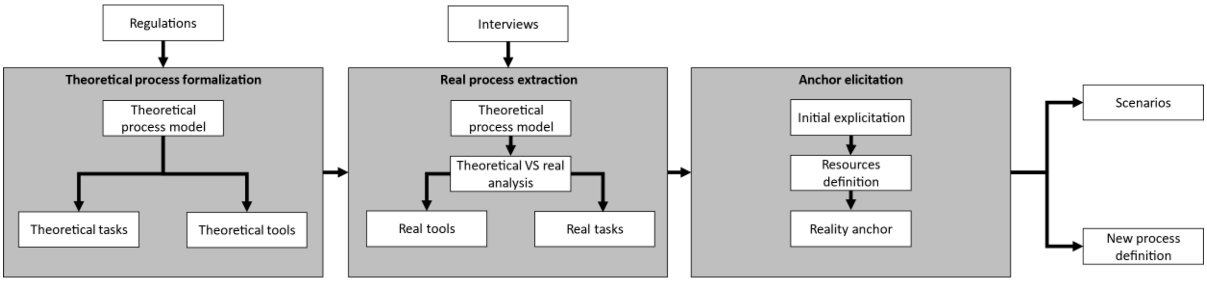

Figure 1. Methodology applied for DT design.

REAM has been implemented on the case study and is detailed thereafter.

4.2 Theoretical process formalization

Company operating procedures are standardized processes based on years of experience feedback to define safe ways to conduct a process in different contexts. These regulations describe the recommended processes for operators and the prescribed tools. The first step of the REAM is to formalize these processes as a temporal sequence of tasks and choices using a visual formalism such as BPMN (Kunz et al. 2010). In our experience most of the tasks described in the regulation are related to the use of the prescribed tools.

For the case study this step resulted in the study of "Company Rules" and "Guides and Manuals" of the company TOTAL. The theoretical process is extracted from these documents (Figure 2).

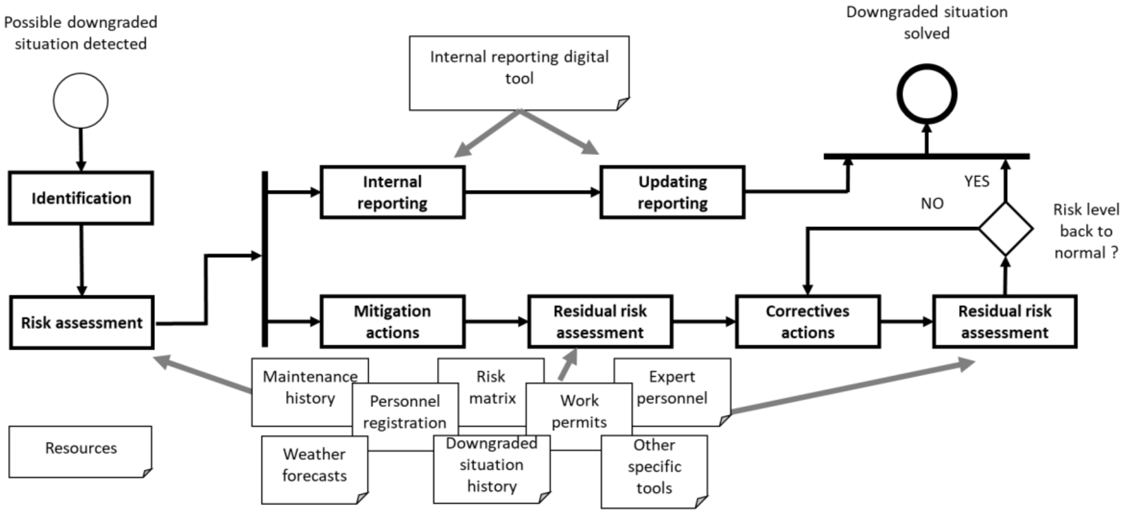

Figure 2. Simplified representation of the theoretical downgraded situation management process with resources used.

This process is carried out by a team composed mostly of the Health Safety Environment (HSE) manager, the OIM (Off-shore/on-shore Installation Manager), and the possible support experts contacted if necessary on the basis of the information transmitted from the CR. The process starts with the detection of a possible downgraded situation and is directly followed by the identification and assessment of the risks. The risk assessment is performed using all available resource including, for example, maintenance history, downgraded situations history, work permits currently in effect representing ground operator activity, or experts' opinion.

Once the risk has been assessed, the first temporary mitigation actions can be defined and implemented. The risk is then reassessed, and the definitive corrective actions are implemented to bring the risk back to its base level. Concurrently, all mitigating actions are reported on the internal reporting tool.

This process is considered as an optimal process in terms of available information, knowledge, and tools. While regulation provide an insight on the tasks and resources to be used for downgraded situation management by a dedicated team, they might differ from performed tasks. The formalized process is then confronted with experts for validation.

4.3 Performed process extraction

The differences between the prescribed process and performed process are used to guide interviews with field experts of the case study. These interviews focus on extracting the resources used as well as exploring the differences between the theory and reality. To acquire this knowledge, the interviews are conducted following a defined protocol by (Unger and Chandler 2009).

This protocol implies semi-structured interviews to give the interviewees the freedom to express themselves without bias. The interview guidelines are based on general themes and introduced by simple questions.

The interviews are performed with three main goals:

- To formalize the performed process to use it as a more precise guideline,
- To collect the needs and ideas of users to use them later in the design process,
- To involve the end-users in the design process to gain adhesion for the human-in-the-loop simulations.

The interviews are recorded and transcribed to ease the analysis and to formalize the performed process in the same format as the theoretical process (Figure 3).

Regarding the DT design the interviews have been performed with users implied in the theoretical process. The themes aborded during the interviews were:

- The tools used to tackle downgraded situations,
- The data available on current tools and the data that is used, the actions conducted when managing downgraded situations,
- The knowledge and how it is accessed and transmitted,
- The human interactions.

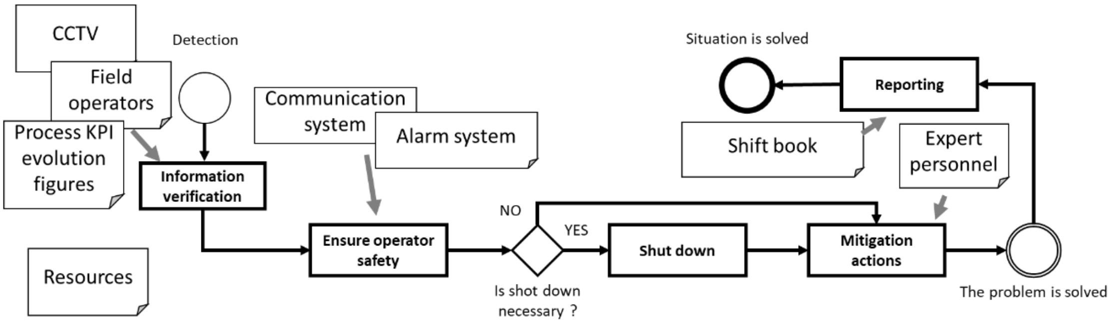

Figure 3. Simplified representation of the performed downgraded situation management process in control rooms with resources used.

The performed process (Figure 3) highlights the specificities of the user process compared to the general theoretical process. While the main tasks remain (identification, risk assessment, actions on the system and reporting), some differences in the order of operation, resources involved and available tools emerge.

These differences are mainly due to the time constraints being more restrictive in the performed process. The users report that the high number of information stored in the information medium makes the selection process too long. Another difference is that the report is filled in on the physical medium after the situation has been resolved rather than during the action process.

Therefore, it can be claimed that:

- The DT must give access to the theoretical process information as well as the specific information used by operators,
- The DT must give access to the information currently shared by field operator using new sensors to enable remote management under similar condition as today,
- The DT must store and share knowledge currently held by expert personnel and allow communication with experts if necessary,

- The DT should enable reporting to be performed on the internal reporting tool once the situation solved to enable experience feedback learning,
- The DT must consider the operator cognitive load in term of shared information.

From this first conclusion, identified tasks can be sub-defined in cognitive functions to model the cognitive sequence performed by the user.

4.4 Anchor elicitation

The Cognitive Function Analysis (CFA) method consists in eliciting human cognitive functions, typically used to perform needed tasks (Boy 1998). These functions are usually identified through the analysis of the differences between the tasks to be performed and the performed activities. However, during the design of a system, activities cannot be observed but only projected. Cognitive function elicitation enables to formalize how data is acquired, information is treated, and knowledge is managed. This methodology emphasizes the identification of reality anchors as physical or cognitive resources that enables the operators to apprehend the reality in her activity.

Tasks are decomposed into potential activities and are incrementally generalized. Cognitive functions are progressively elicited. Each cognitive function is then associated to:

- Physical resources, i.e., tools or support used to execute the function. For example, the cognitive function "reading this article" is related to the physical resource "display medium (the paper or screen you are using)").
- Cognitive resources, i.e., other cognitive functions or cognitive entities needed to use the function. For example, the cognitive function "reading this article" is related to the cognitive resource "understanding the English language").

Figure 4 is an example of the first stage of the application of CFA to the information verification from the performed process presented in Figure 3.

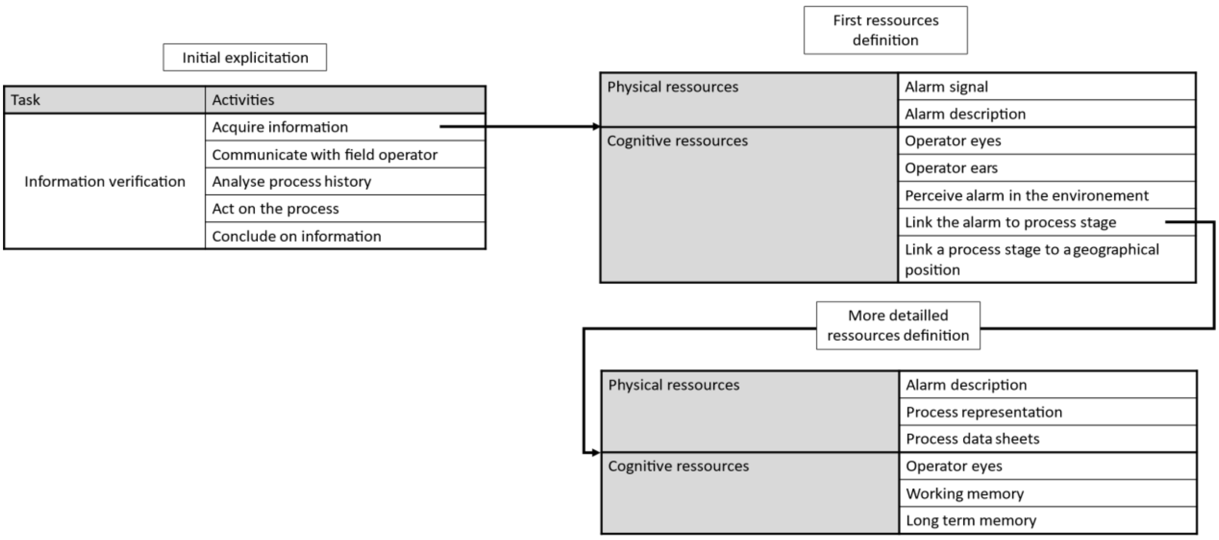

Figure 4. Cognitive function analysis of the "information verification" task extract.

This task is first decomposed in 5 potential activities:

- Acquire the information: The CR operator becomes aware of an alarm and identifies its nature.
- Communicate with field operators: The CR operator contacts the relevant field operator to get some context information from the field.
- Analyze process history: The CR operator refers to values (e.g., pressure, temperature…) from the process history to corroborate some information.
- Act on the process: The CR operator uses actuators from the process to test some hypothesis about the process behavior based on situation projections.
- Conclude on information: The CR operator draw conclusions on the situation based on the complementary information acquired.

The cognitive function analysis allows to identify the resources used by the CR operator to perform those activities. Taking the example of the Acquire the information activity, the physical resources are defined as:

- Alarm signals: Audio and/or visual signals that can be perceived by the CR operator.
- Alarm description: The alarm quality defined and shared with the CR operator.

The cognitive resources are defined as:

- Perceive alarm in the CR environment: The alarm signal must be perceived by operator.
- Link the alarm to a process stage: The CR operator needs to be able to link the alarm signal to a specific process stage.
- Link a process stage to a geographical position: The CR operator needs to be able to locate the geographical area concerned by the alarm.

At this stage, a first set of reality anchors can be defined. The alarm signals and its description are what link the CR operators with the reality on site. They are the first evidences of an issue that needs to be addressed. However, they are not the only resources that anchor the CR operator. Other cognitive functions have appeared and can be in turn explored and associated with resources. Figure 4 shows the results of the analysis of the “link the alarm to a process stage” as an example. The physical resources defined as required for this function are the following:

- Alarm description: As defined in the previous analysis step.
- Process representation: To model the process, a formatted representation is available to the CR operator.
- Process data sheets: Information related to the process that cannot be displayed on the representation are available in data sheets.

The cognitive resources needed are defined as:

- The operator vision/sight.
- Working memory.
- Long term memory.

At this stage of the analysis, the cognitive resources describe the basic cognitive functions that have an impact on the performance of the task. A sufficient level of detail is considered to have been achieved. The set of reality anchors has been extended to include the dynamic representation of the process which is the CR operator's entry point to what is happening on the site.

Once this detailing process is performed for every tasks, the projected activities and associated cognitive functions are elicited and the resources enabling the operator to relate to reality identified. The role of these reality anchors is discussed in the following section.

5 DISCUSSION

We have defined an iterative method to detail a work process at a level of granularity that highlights what enables the user to interact with the system for which we are designing a DT called the REAM. The detail is performed by identifying the physical elements and cognitive resources needed to perform an activity. These cognitive resources are cognitive functions themselves, with their own resources. The specificity of our method concerns the identification of resources enabling an operator to model the reality and to understand the situation.

In the case study we have performed, several sources of anchors have been identified:

- System interactions
- Dynamic representation of the system
  - Physical values
  - Systems and sub-system states
- Human interactions
- Meta-information about the context.

In order to design a DT that allows its user to understand a downgraded situation, those sources must be available. The REAM develops by iteratively checking the identification and validity of the anchors between users and their environment through human-in-the-loop simulation. DT are by definition the representation of a real system to be managed. To enable human-in-the-loop simulation without a real system existing these sources need to be simulated.

Physical values usually come with the system definition and art part of the first data available on systems. These values are fixed and can be implemented in the DT without the system existing.

The system and sub systems states are evolving throughout the process. These states are simulated through numerical simulation in standard human-in-the-loop designing methodology.

Human interactions can be simulated using actors with working experience. In the case of radiocommunication, the interaction can be performed realistically using similar radiocommunication systems as the actor voice is the interaction medium. When face to face, the actor body becomes the medium as well and attention to detail is needed in order not to break the reality flow around the user. Meta information related to the context can be considered as fixed point in reality if related to a specific event or evolve along time when related to unplanned events. In both case they can be simulated and implemented in the DT following specific scenarios. The interface component of the DT will have to be studied and defined as well to ensure information are transmitted from and to the operator correctly.

6 CONCLUSION AND PERSPECTIVES

Following a human-system integration approach, the methodology introduced in this paper focused on defining the anchor points between DT users and the managed system to guide its design and enable human-in-the-loop simulations. The methodology follows three incremental steps which are (1) the process theory study, through the regulatory study which defines the baseline of existing resources and ideal tasks, (2) the realized process study, through user interviews, which defines the tasks performed by the users and the physical and cognitive resources used and (3) the cognitive function study to identify the cognitive resources related to the system.

The REAM is currently being applied to the design of digital twins for oil and gas facility management. It highlights field operators, system models and technical databases as reality anchors.

These reality anchors will be implemented in a prototype TD to replace its physical counterpart. Further tests with the prototype, after a human-in-the-loop simulation, will allow to study the activities performed by the operator and to validate the potential activities obtained in phase 2. Anchor elicitation will be validated and iterated to identify missing anchors.

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