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Reality Anchor Methodology: How to Design a Digital Twin to Support Situation Awareness

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Abstract: This work focuses on the opportunity to use the Digital Twin of a complex system, as a Decision Support System. In studying the phenomenon of human Decision Making, the concept of Situation Awareness appears to be of primary importance when dealing with these complex systems. Given the complexity of the system to be represented in the DT, its own complexity, and the need to integrate the user's abilities to allow the acquisition of SA, the concept of reality anchor is proposed to identify the elements of the studied situation necessary for users to perceive, understand and project the situation they face. A methodology, called the Reality Anchor Methodology, has been defined to ensure the elicitation and implementation of these elements in a DT. This methodology is composed of three steps that aim (1) to elicit the reality anchors through a study of the operators' tasks and activities, (2) to design a prototype to carry out human-in-the-loop tests and (3) to validate the definition of Reality Anchors by analysing the SA, experience feedback and the activities performed during the tests. This method was applied to a case study in the oil-and-gas industry and showed the importance of the defined reality anchors.

Keywords: Human Systems Integration; Digital Twin; Situation Awareness; Design methodology; Complex systems

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Introduction

Industry 4.0 proposes responding to the growing complexity of industrial engineering by improving the management of those complex systems through the use of new technologies. In the field of systems engineering, a complex system is defined as “a group or organisation which is made up of many interacting parts” where “the interactions between them often lead to large-scale behaviours which are not easily predicted from a knowledge only of the behaviour of the individual agents” (Mitchell and Newman 2001). Different approaches to complexity have been proposed to better understand complex systems (Manson 2001). Algorithmic complexity mathematically evaluates the complexity of algorithms used to represent the system’s behaviour. Deterministic complexity uses main elements of the system to represent its complete behaviour and define its entire complexity. Aggregate complexity aims at defining every component of the complex system and the interactions between each component. This theory is time consuming because it aims to define many components and interactions, but it is the most holistic approach to complex systems. This last approach to complexity is the one followed in this work as it is believed to be more relevant to take humans into consideration and apply an HSI approach.

As part of these new complex systems enabling data collection and actuator control, the Digital Twin (DT) paradigm represents the full industry 4.0 remote management capabilities. This paradigm replaces current in-use industrial information systems to provide more developed system management. DTs were initially defined as perfect Product Lifecycle Management (PLM) tools (Grieves 2014) consisting of three components: (1) a physical system, (2) a virtual system and (3) the flow of data between them. Many other definitions were proposed based on different points of view (Datta 2016; Negri et al. 2019; Madni, Madni, and Lucero 2019; Mihai et al. 2022; Hartmann 2021). However, none of them considers the importance of humans as DT users or as part of the complex system. Therefore, in (Camara Dit Pinto et al. 2021), DT is defined as 'a dynamic representation of a physical system and its environment using interconnected data, models, and processes to enable access to knowledge of past, present, and future states to manage actions on that system'. This definition is accompanied by a framework composed of six main components (see Figure 1) that are (1) the situation model that represent the situation, (2) the sensors data that collect data from the physical twin, (3) the interface that enable human communication with the DT, (4) the data management that allows to reduce, select or process the available data, (5) the memory that store the data and information, and (6) the actuators that act on the physical twin and differentiate it from a digital shadow or a more common digital model (Kritzinger et al. 2018).

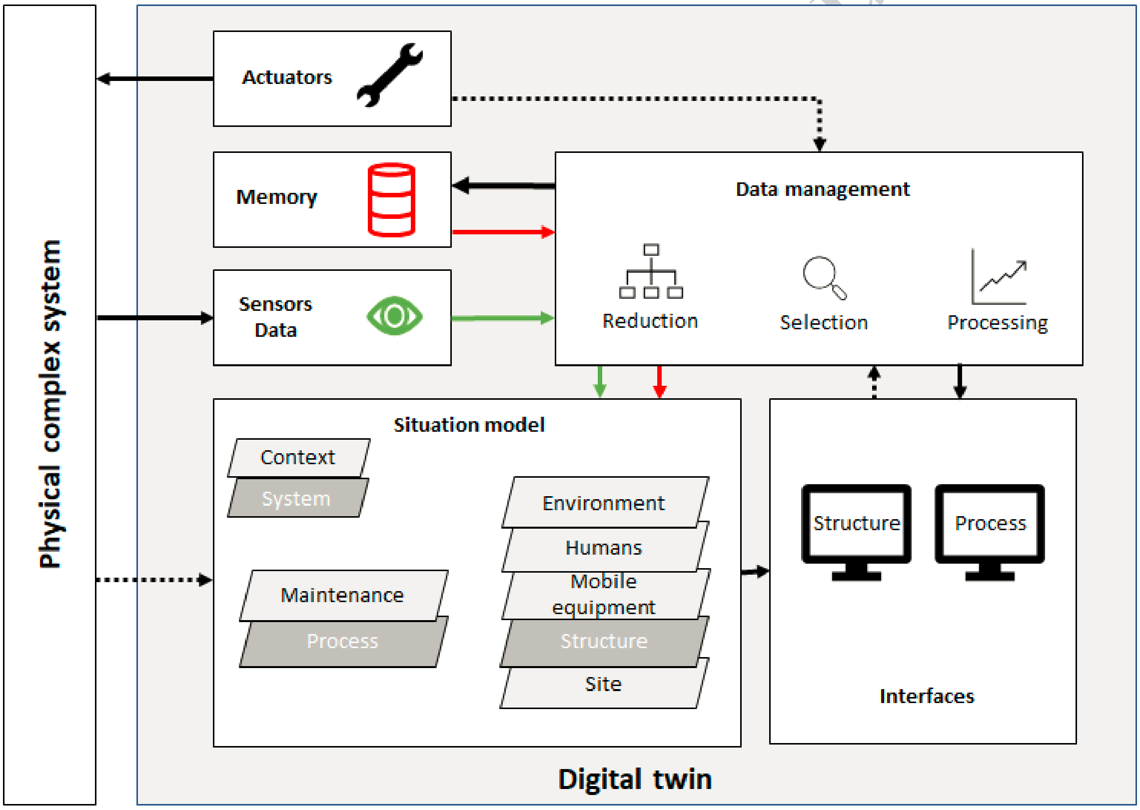

Figure 1 - The digital twin and its components

Even if using a DT is enabling the management of a complex system, it is not an easy task and decision making is constantly involved. Some work focussed on the automation of the decision through DTs have been performed (Mohammed et al. 2022), however, this work focus on human decision making. Theories regarding decision making emerged from multiple fields focusing on the selection of '*the best option from a choice set containing two or more options*' (Beach 1993). Different models have been developed to characterise this human capacity. Several types of decision-making processes have been defined in literature. From the psychology domain, Rest's four-step model (Rest 1986) appears as a strong basis. The four-step model consists of (1) the recognition of the moral issue where the awareness of the moral situation must be made, (2) the formulation of a moral judgement, (3) the establishment of moral intents, and (4) the engagement in a moral behaviour. In the engineering domain, Mintzberg developed a model called the organisational decision-making model (Mintzberg, Raisinghani, and Theoret 1976). This model (see Figure 2) is developed to be adapted to different cases, but three main parts are common to every decision: (1) the identification of a given decision to be made, (2) the development of a solution, and (3) the selection of the associated decision. During those three steps multiples other actions are performed that enable humans to make the best possible action.

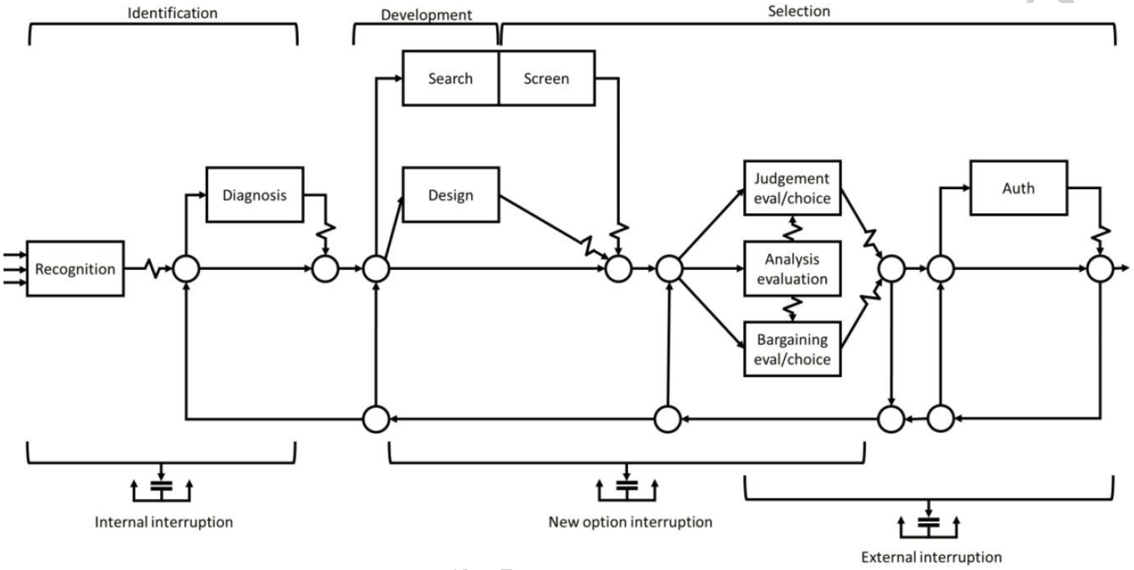

Figure 2 - Organisational decision-making process.

While dealing with complex systems and human Decision-Making (DM), Endsley emphasised the importance of Situation Awareness (SA) (Endsley 1995). Human SA, as an individual human phenomenon, is defined as 'the perception of elements in the environment in a volume of time and space, the comprehension of their meaning, and the projection of their status into the near future' (Endsley 1995). It can be broken down into three levels (see Figure 3): (1) perception, (2) comprehension, and (3) projection. This definition of human SA was transposed in the engineering community as a set of data and information collected in a technological system (ESRI 2008).

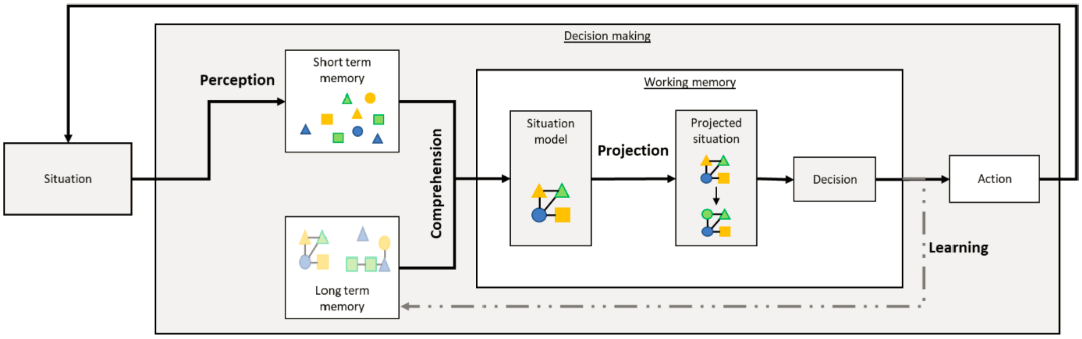

Figure 3 - Three level situation awareness model.

However, the distributed SA concept (Stanton et al. 2006) proposes considering humans and systems as agents who have their own SA that is distributed among these. Following this cooperative vision of SA, through the concepts of decision-maker and DT interaction for remote management, it appears that there is a need to “tangibilize” (Boy 2013) reality through the DT. It is therefore important to provide users with elements of the situation to enable them to make informed decisions (Abi Akle, Yannou, and Minel 2019) and work have been and is being performed in this direction (Sui et al. 2023). According to this principle, the concept of RA is defined as “*useful elements of the situation necessary for humans to enable them to grasp reality and acquire a meaningful SA that supports the DM process*”. The elicited anchors are then used as guidelines for modelling the situation in the DT.

First, as shown in (Larrasquet, Pilnière, and Jayaratna 2016) implementing innovative processes must be supported by a user-centred methodology to accompany users. Therefore, ensuring the correct and repeatable implementation of a complex system such as a DT requires using a specific methodology. A study of the digital twin design methodologies available in the literature shows a focus on methodologies oriented to the technical implementation of a DT. However, as a DT is defined to enable a user to ‘manage actions on that system’, it is important to ensure the implementation of the Reality Anchors (RA) to support situation awareness. Due to the lack of user-centred DT design methodologies, such a methodology, called Reality Anchor Methodology (RAM), is proposed to develop a DT validating human SA requirements. Finally, the RAM is applied to an oil-and-gas use case to validate the proposed methodology.

Related work

DTs are complex systems composed of multiple elements (Camara Dit Pinto et al. 2021). Designing such a complex system requires a methodical process. In the literature, multiple methodologies are proposed to design a DT.

In (Negri et al. 2019), the authors proposed a six-step methodology for the implementation of a states-based DT. In this methodology, the first step aims to identify the states and variables to be implemented in the DT. Then, the system's model is developed one piece of equipment at a time. Subsequently, the models are connected to the data sources on the real system. Finally, the data flow is analysed and adapted to correspond to the real system's behaviour. At this point, the DT can be finalised and connected to a simulation model.

In (Qamsane et al. 2021), the authors proposed a DT implementation methodology based on the System Development Life Cycle. The defined methodology consists of five stages. The first stage focuses on planning the implementation, starting by defining manufacturing needs. Key Performance Indicators (KPI) are then defined to ensure the ability of the DT to satisfy the identified needs. In stage two, the requirements are defined. The assessment of the DT requirements is performed both qualitatively and quantitatively to define the best DT solution alternatives. Once the best alternative is selected, the solution is documented. In stage three, the DT is designed. During this stage, individual Object-Oriented DT are developed and connected based on an Object-Oriented model. The model's consistency is then checked. In stage four, the DT is fully implemented. In stage five, the developed DT is tested against the defined requirements.

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In (Pérez et al. 2020), the authors proposed a four-step methodology with feedback loops to create a DT. The first step, design, aims to analyse the requirements, and to define the robotized process to be used with the DT. Based on this defined process, a virtual reality model is defined that takes into consideration the robots, and other components, the actions and events, and a simulation to validate the defined process. Once validated, the defined process is implemented, and the virtual reality model is updated accordingly. Finally, they can be implemented by installing sensors and visualising in real-time. This methodology was applied in the case of collaboration between humans and robots in a manufacturing process.

In (Aivaliotis et al. 2019), the authors proposed a three-phase methodology for physics-based modelling. The first stage of the methodology focuses on modelling the physical system's dynamic behaviour. The resulting model is based on kinematics and structure. The second stage of the methodology focuses on modelling the virtual sensors used to recover data from the physical system to the virtual system. This stage consists of selecting information and modelling a virtual sensor to be integrated into the system model. Finally, the third stage defines the system parameters that enable the physical and virtual systems to be mode finely tuned. This methodology has been applied to a use case about an industrial robot.

This methodology enables multiple components of a DT, such as a system model and the related sensor data, to be implemented and ensures the tuning of the model with reality.

Looking at those examples of multi-step digital twin implementation methodologies, a general design process can be identified. First, the system is studied to identify the DT requirements. Then, the virtual model is implemented one component after another to create a complete system model. Once the model is created, the data from the real system is used in the virtual model and the quality of this data flow is validated. In some cases, like in (Qamsane et al. 2021; Pérez et al. 2020), special attention is paid to studying the system to correctly define the DT's technical requirements. This shows the importance of implementation planning and ensures that the results can be compared to the end results like in (Pérez et al. 2020). In some other cases, like in (Aivaliotis et al. 2019), the focus is on the type of different models used which make up the full system. In an ideal methodology, all these steps should be developed to enable any future designer to adapt the methodology to the selected industrial application.

However, these methodologies, and others, do not take into consideration the role of human agents in their interaction with the DT. Failing to consider this aspect may end up with the implementation of a DT that does not satisfy users' needs (Boy 2013). Moreover, if the physical model is defined, its impact on its environment is not taken into account. This would go against the acquisition of situation awareness that is prevalent in the context of DM on complex systems. Moreover, DTs remain interactive systems and should follow recommendations in User-Centred Design. Therefore, this study proposes defining a methodology for DT implementation that puts users at the centre of the design process by ensuring the implementation of the RA. Such a methodology should propose identifying SA requirements, use DT-based simulation to evaluate the impact, and iterate to reach a satisfactory solution.

Proposed methodology

The RAM (Figure 4) proposes eliciting useful elements of the situation necessary for humans to enable them to grasp reality and acquire a meaningful SA that supports the DM process in a Decision Support System. Moreover, this methodology aims to support designers (systems engineers, human factor specialists, etc.) to implement these elements in a DT to ensure decision-makers' SA.

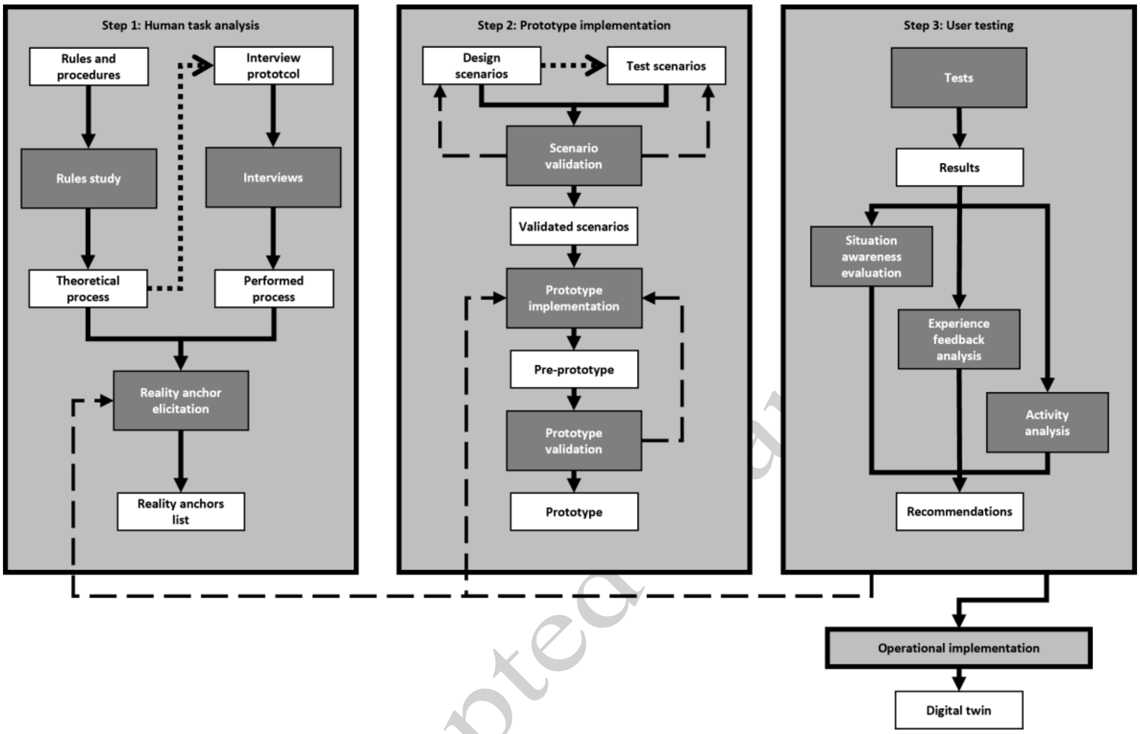


Figure 4 - Reality Anchor Methodology implementation process

The methodology consists of three main steps which are (1) the analysis of user tasks to identify reality anchors, (2) the implementation of a prototype, and (3) the validation through human-in-the-loop testing. The human-in-the-loop tests enable to analyse activities performed and identify the RAs used in the DM process or those missing from the DT. This analysis allows iterating on the anchor elicitation if necessary to ensure the best human SA.

At the end of this process, the DT can be implemented with all the RAs corresponding to the task to be performed and therefore provide SA to users. This methodology can be used to design DTs that have not had previous iterations or to improve an existing DT.

Human tack analysis

In the human task analysis step (cf. step 1 in Figure 1) the designer focuses on understanding user needs in terms of SA to provide the elements necessary to perceive, comprehend, and project reality in the DT (i.e., to make the DT more tangible). This analysis is broken down into three steps.

The formalisation of the theoretical process focuses on the analysis of the company's regulations to extract a recommended decision process. Companies usually implement rules and procedures to standardise practices and reduce errors (Hale and Borys 2012).

These regulations can be rules, processes, or advisory documents. They are implemented based on experience and are expected to be known and followed by everyone in the company. The regulation review is aimed at finding regulatory documents related to the DM situation tackled by the DT.

Through this step, the designer acquires knowledge about the tasks to be performed and identifies recommended sources of information. The identified DM model that can be extracted from the documents can be formalised using the Business Process Model and Notation (BPMN) (White 2004) to represent and interconnect agents, events, tasks and information sources.

Since no document focuses specifically on the specific DM situation to be supported and because differences between the tasks of the recommended decision process and the User eXperience (UX)-based decision process are known (Hollnagel 2015), interviews with current or future decision-makers allow a decision process to be extracted that is closer to the operational reality. These interviews can focus on the decision process thanks to the knowledge acquired during the recommended theoretical process.

It is recommended that these interviews be performed according to a semi-structured interview protocol. Semi-structured interviews consist of open-ended questions. The main categories of interests in the field should be identified, but the use of open questions gives users the freedom to refine their answers with their knowledge of the field. Other questions, which are improvised from the answers provided, can be asked to further the interview. This interview model assumes moderate knowledge of the domain to identify question categories and allows the domain to be explored while maintaining specific answer objectives.

Finally, the performed process extracted from the interviews is then analysed according to a Cognitive Function Analysis (CFA). Cognitive functions (Boy 1998) are defined from the identified tasks of this decision process and are by definition composed of a role, a context and physical and cognitive resources used to transform a task (i.e., what is prescribed to be performed) into an activity (i.e., what is effectively performed). The resources related to carrying out these tasks in real-life allows RAs to be defined.

Making these elements of the situation accessible to the user should enable SA through the DT. The next steps aim to implement a prototype and test it to evaluate the ability of the DT to support SA.

Prototype implementation

In the prototype implementation step (cf. step 2, Figure 1) the designer focuses on designing a DT prototype that contains the previously identified RAs. This implementation is done using a human-centred iterative design process that takes from User-Centred Design/Human Computer Interaction (HCI) well-known practices such as Scenario-Based Design and Wizard of Oz simulation. This process is used to ensure that the DT addresses both usability and display of the RAs identified in the previous step. This implementation involves six steps.

First, the definition of design scenarios is based on the ‘Scenario-Based Design’ concept (Carroll 1997). Instead of making evolution on a prototype, scenarios are evolved and refined through an iterative process. These scenarios are used to describe the user's possible interactions with the system in order to ensure their implementation.

Once the design scenarios are defined, specific testing scenarios are defined to be implemented in the prototype for future testing based on the design scenarios. These testing scenarios are reviewed and refined through an iterative process. These testing scenarios are defined based on the behaviour to be studied. Therefore, they should focus on information accessibility, quantity and validity. In addition to these scenarios, a training scenario should be defined to be different from the testing scenario and to ensure the understanding of most of the prototype's functionalities.

Finally, the prototype is implemented based on the interactions identified through the design scenarios that integrate the defined reality anchors throughout the validated testing scenarios. To perform realistic tests with users without implementing the full complexity of a DT, an adaptation of the ‘Wizard of Oz’ concept can be used (Dahlbäck, Jönsson, and Ahrenberg 1993). ‘Wizard of Oz’ comes from the field of HCI in which advanced functions are performed by a human invisible to the participant. This concept can be enlarged to develop a two-person tool where one can control the system without the other one knowing. This would make it possible to make the testing user believe that the complex system is really functioning without fully implementing it (Cross 2018).

The implemented prototype is itself reviewed and refined with user feedback to improve the usability of the User Interface (UI) and ensure the realism of the implemented tool.

At the end of the second step, the prototype contains all the extracted critical elements necessary for SA acquisition and is ready to be evaluated for its SA acquisition capabilities. This evaluation aims to assess the ability of the DT to provide SA to the user.

User testing

In the user testing step (cf. step 3, Figure 1) the designer focuses on validating the reality anchors that affect SA in the prototype. The validation is performed using three analyses: (1) SA assessment, (2) feedback analysis and (3) activity analysis.

The test protocol used aims to make the tests repeatable, as well as flexible due to the nature of complex systems. This flexibility is ensured by using the ‘Wizard of Oz paradigm’. Performing tests using this paradigm means that the designer/wizard can adapt the interaction of the complex system if needed and even take the role of a co-worker if the need for new interaction emerges.

The protocol starts with an introduction to the project and a role-playing phase to ensure the user is immersed in the situation. Then, a training scenario is used to familiarise the user with the prototype. To ensure a complete learning experience, a set of specific queries can be used to encourage the user to perform possible interactions. During this phase, every question from the user regarding interactions with the prototype is answered. Once the testing user is familiar with the tool, the test scenarios are played. Each scenario ends with a personal evaluation of the SA and the submission of a feedback form. During the tests, the activity must be recorded either through an expert evaluation, or through the recording of interactions performed on the UI, or through the analysis of an ’eye-tracking’ type recording. At the end of the tests, an analysis of the results is performed to make recommendations.

Situation awareness assessment

Several SA assessment techniques can be found in the literature, such as SAGAT (Endsley 2000) or SACRI (Hogg et al. 1995). The Situation Awareness Global Assessment Technique (SAGAT) (Endsley 2000) is an assessment technique that operates on the principle of querying the frozen screen. As the tool is tested and the situation is presented, the prototype freezes the screen at a specific point in time and provides queries to the user to reflect the three levels of SA. Similarly, in the Direct Questioning Technique (DQT) (Stanners and French 2005), derived from SAGAT, the questions are developed based on a Goal Direct Task Analysis and with the support of subject matter experts to reflect the situation awareness requirements for decision making. While SAGAT uses a set of queries, the DQT only uses six verbally asked questions. SACRI (Hogg et al. 1995), also based on SAGAT, focuses on control room alarm management. The questions are randomly selected and offered to the user through the interface during a set of scenarios lasting at least 30 minutes. Another technique, called SALSA (Hauss and Eyferth 2003), proposed to follow a similar protocol to SAGAT with addition of a replay evaluation by experts. However, since the human-in-the-loop testing step of RAM aims to ensure the correct elicitation of RAs, it is not possible to use these techniques that require having a list of useful SA elements in advance. This is why the Situation Awareness Rating Technique (SART) (Taylor 1990) is recommended to perform this assessment. Indeed, SART provides a subjective picture of SA in the different scenarios based on expert users and does not focus on an objective assessment of the quality of SA. To use the SART, it is important to compare the criteria to the expected values. On the one hand, the criteria regarding the situation should be related to the defined scenario. For example, a scenario made to be complex should be evaluated as more complex than a simple one. On the other hand, criteria regarding the user should be evaluated based on the expected answers. If the results do not align with the expected results, post-test interviews can shed light on the reason for this difference.

Experience feedback analysis

The analysis of experience feedback is performed using three types of experience feedback forms that will provide different levels of details in the description of the situation.

The first type of experience feedback is inspired by shift books used in continuous production domains. It is a free expression support whose purpose is to record the situation experienced and share it with other users. It usually contains expert vocabulary and focuses on the most important information needed to understand the situation without sharing detailed information and reasoning. This experience feedback contains the RAs needed for a basic understanding of the situation and is thus considered a major concern for the user's SA.

The second type of experience feedback is more directive with three categories of questions. (1) The user is asked to describe the situation. The objective is to identify the main RAs used to describe. This part of the feedback focuses on the perception level of SA. (2) The user is asked to analyse the situation. The objective is to encourage the user to provide information related to their understanding of the situation. (3) The user is asked to explain the action taken to resolve the situation. The objective is to encourage the user to provide information related to their projection of the situation. This directed experience feedback aims to gather knowledge about the role of RA in the three levels of the SA process.

The third type of experience feedback is query-based. To validate the user's ability to find information in the prototype, a third type of questionnaire is provided. This questionnaire asks the user to provide information related to reality anchors and SA. Providing this information correctly ensures the user's ability to find information in the tool and generate knowledge on the situation. This indicates their ability to achieve the three levels of SA and the quality of their SA.

Activity analysis

The analysis of activity allows the information consulted by the user during the DM process to be capitalised on. Therefore, RAs used during the tests are elicited and missing anchors are identified through the voice recordings and debriefing phase. The process of acquiring SA is compared to the results of the interviews. This activity process, once compared, highlights missing RAs and enables a final decision process for the user tasks to be defined. The process also shows emerging behaviours and sub-task division enabling a better understanding of the human DM process. Moreover, it highlights the useless anchors to be removed to avoid overloading the UI.

Based on the results from these three analyses, recommendations are elicited. These recommendations can be associated with the implementations of the RAs (which ones are missing or not needed), the UI design (which important RA need to be highlighted or hidden) or related to future evolutions of the information form to represent the RA at best. These recommendations are then implemented into future iterations of the prototype.

Use case application

The use case studied was based on one of the industrial activities of the exploration and production branch of TotalEnergies. To select a coherent industrial use case, three factors were considered: (1) the site on which the decision would be made, (2) the configuration of the site, and (3) the downgraded situation on which the decision must be made as the company policy is to reduce as quickly as possible the risks from those situations through immediate actions.

The site selected for this study is a fictive Floating Production, Storage and Offloading facility (FPSO) based on a FPSO vessel from TotalEnergies company. This study focuses on a two-stage separation process located in section S7 of this FPSO. This two-stage process is a usual process familiar to the operators that enable its realistic replication in a prototype. The process equipment is distributed over a three-floor section of the FPSO which had to be fictitiously equipped with sensors according to internal rules and procedures.

The process chosen for this study is a two stages oil and gas separation process. This process is standard on Exploration and Production (EP) sites and is therefore well known by control room operators. Moreover, this process uses separation tanks (cf. high-pressure separation tank in Figure 5) fitted with flanges which joints are known as the potential origins of gas leaks. The use of the separation process is therefore coherent both in terms of anomaly realism and operators' working conditions. This process consists of a high-pressure stage and a medium-pressure stage.

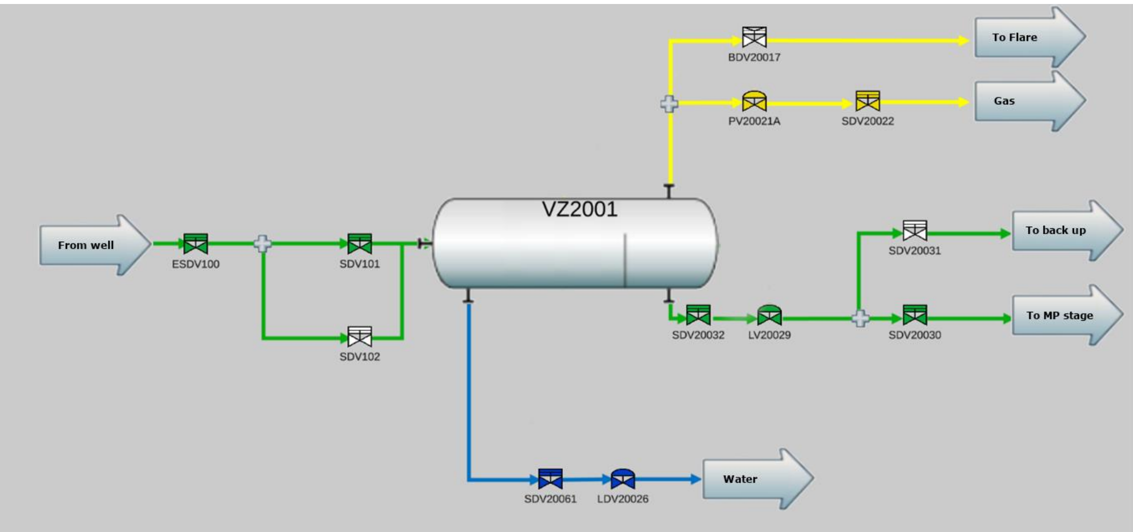


Figure 5 - View of the high-pressure separator and the associated control valve selected as use case

The process equipment is situated in section S7 of the FPSO. This part of the FPSO has three floors: (1) the process deck (cf. process deck section in Figure 6), (2) the mezzanine deck and (3) the upper process deck. In addition to the process equipment, these floors are equipped with acoustic sensors, standard gas concentration level sensors (in green in Figure 6) and Close-Circuit Television (CCTV) (in purple in Figure 6) systems. To be realistic, these elements had to be implemented on the layout in accordance with regulations as if they were implemented in real life.

Working with the TotalEnergies safety Research and Development (R&D) projects looking to improve DM during gas leak management, the studied downgraded situation selected was a CH4 gas leak on a separator. Additional factors of the situation, such as the presence of people in the vicinity or changing weather conditions were selected to create a realistic complex downgraded situation.

All these features lead to a use case for the RAM to be implemented with the aim of designing a digital twin of this industrial use case that could be used as a control room operation system. The following subsections describe the implementation of the RAM to design this DT.

Human task analysis

The regulation study focuses on analysing the company safety regulations to extract a decision process and recommended supports and tools for information acquisition. This study started with the identification of documents related to downgraded situation management. Three relevant documents have been found:

- Health, Safety and Environment (HSE) risk management in operation. This document defines mandatory actions regarding qualified personnel, tools enabling information acquisition as well as work organisation.
- Fire and Gas detection. This document explains and proposes qualified detection equipment, as well as the detection logic.

Figure 6 - View of the process deck of the section containing the high-pressure separator and safety equipment selected as the use case

- Management of downgraded situations. This document sets definitions of the domain concepts, identifies the key personnel involved in the process and details each step of a recommended process for DM.

Even if the documents are not dedicated to describing control room operators’ activities, they describe the general philosophy of the activity.

The process and the associated identified resources have been defined using the BPMN format. Figure 7 shows a simplified version of the theoretical process.

This formalised process of downgraded situation management allows the knowledge acquired relating to general risk management and gas detection logic to be identified. It also provides an overview of the job performed by control room operators. However, the following step focuses on ensuring a detailed understanding of the tasks to be performed by control room operators using interviews.

To validate and detail the users' actual DM process, interviews are conducted, as work as it is imagined differs from the work actually done (Hollnagel 2015). The interview followed a semi-structured protocol defined to record UX on domain-specific topics: the task performed, the tool used, the accessible information, the interaction with people and the acquired knowledge. The transcripts of these interviews were then studied to define a DM process in the same manner as the regulation study.

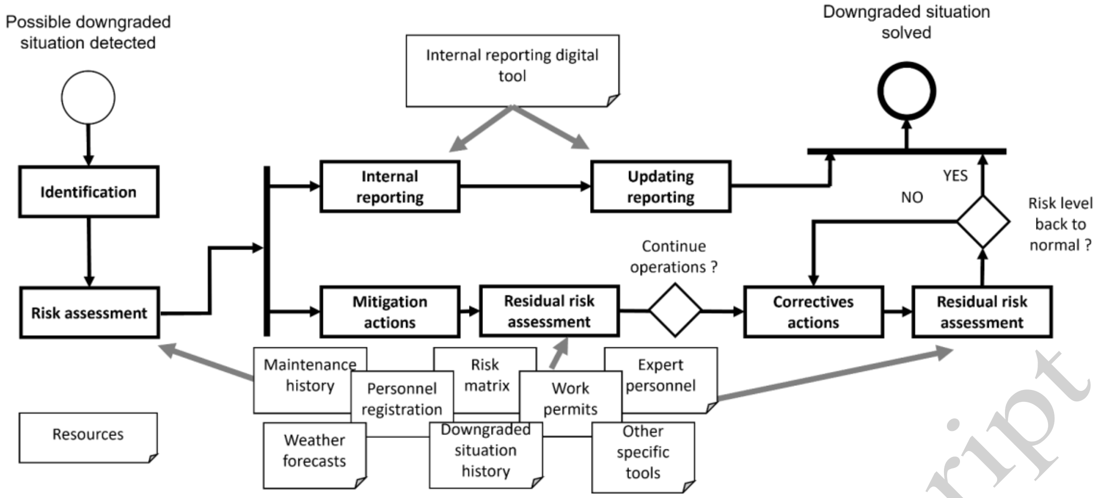


Figure 7 - Downgraded situation management process

The process and the associated identified resources have been defined using the BPMN format. Figure 8 shows a simplified version of the real process in control rooms.

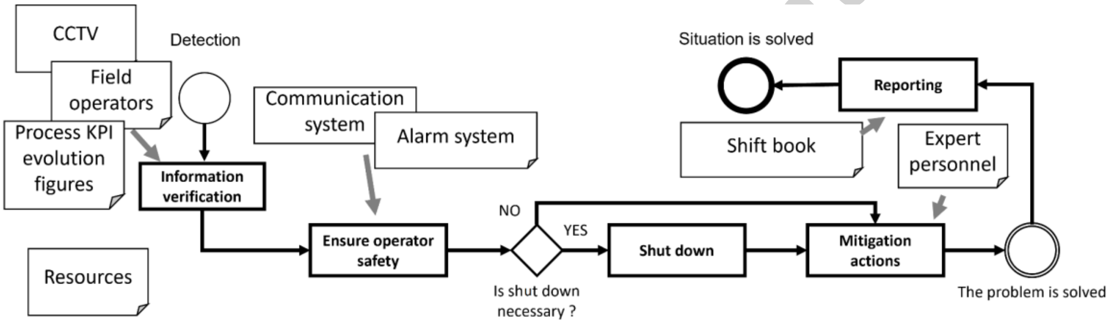


Figure 8 - Management of downgraded situation for operators in control room process

Comparing the real process to the theoretical one, differences due to work situations can be identified. First, due to time constraint differences, the used information sources are different. This is in line with the information obtained during the interviews related to accessible information. These differences can be narrowed down thanks to the ability of DTs to contain information and knowledge in a global tool. Differences also appear in the order and form in which the reporting action is performed. As anomalies must be dealt with swiftly to avoid possible escalation, control room operators need to react in less than 10 minutes and are in charge of first and immediate corrective actions. Therefore, the control-room anomaly management process is shorter, and the reporting activities are performed at the end of the process. Moreover, reporting is done in a free writing format as opposed to the directed reporting form of the global management process, which is done in parallel to problem-solving activities. Furthermore, similarities appeared in the form of the main activities performed showing a global management logic with verification of the information, actions to solve the problem and a report for others to be informed. This confirms the choice to use a DT to enable a more complete situation-oriented DM process. To identify the situation-oriented elements used by operators to acquire SA, a cognitive function analysis is performed on the identified control room DM process.

Once the tasks to be performed have been identified, the cognitive function analysis paradigm (Boy 1998) is used to identify the RAs used by the operators to acquire SA and make decisions. These will then be implemented in the DT to ensure its ability to provide the necessary elements to users to acquire SA. The cognitive function analysis aims to identify cognitive functions used by humans to perform tasks. These functions are defined using a name, a context, and resources both physical and cognitive.

For example, in the "identify the alarm signal" task, the name can be defined as "identifying an alarm signal" in the context of a gas leak detection in an oil-and-gas control room. The resources needed for the user to transform the task into an activity can be identified as the following:

- An audio signal alarm (physical),
- A visual variation on a physical system (physical),
- The "remembering the alarm signal types" function (cognitive),
- The "hearing audio signals" function (cognitive),
- The "seeing a visual signal" function (cognitive).

This definition process must be performed for every task to identify every resource needed by the user to perform its tasks. In this example, two RAs can be defined as an audio alarm signal and a visual alarm signal. As RAs, these signals enable the user to identify that one or more sensors have changed status and detected an anomaly in the situation. At the end of the analysis of the 29 cognitive functions previously identified, a total of 29 RAs were discovered (see Table 1).

Prototype implementation

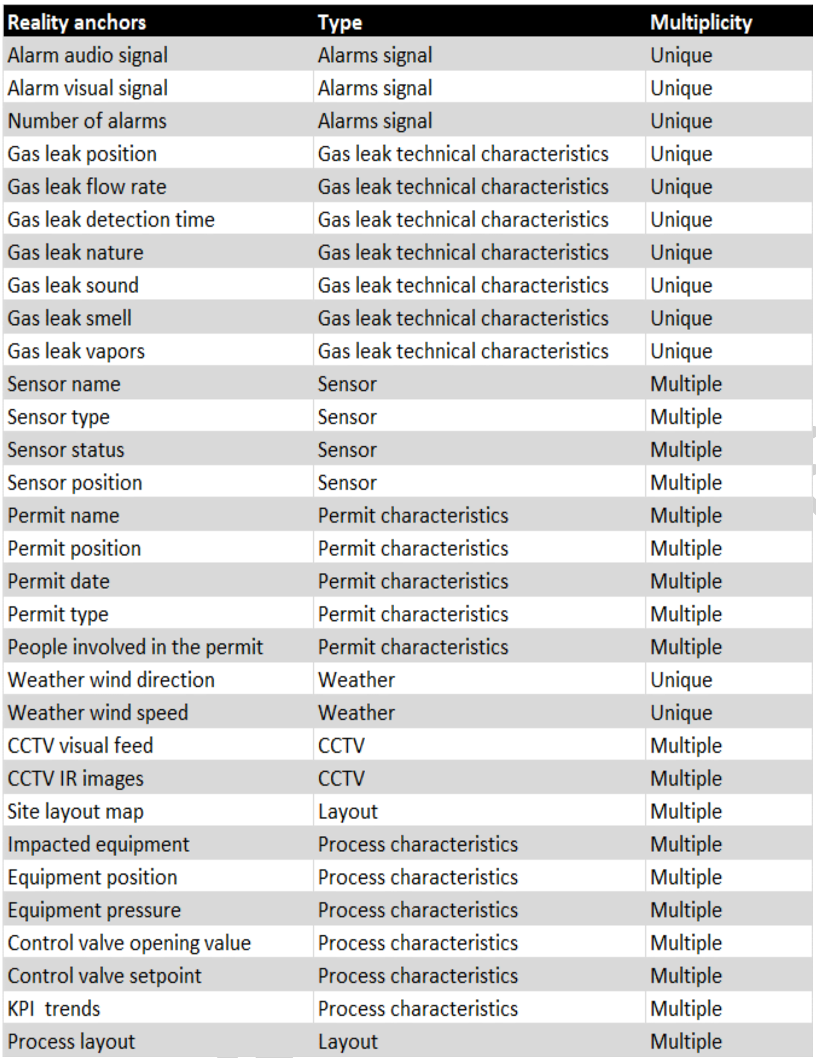
Using the scenario-based design paradigm (Carroll 1997), usability scenarios were defined in an iterative way to describe the prototype's uses. The scenarios are expressed as user stories such as: "Will, field operator, calls the control room to report hearing a leak near the high-pressure separator. Ophelia, control room operator, checks the list of alarms and does not identify any detection, she checks the process values and does not see any significant variation either. She asks Will to distance himself from the potential danger and contacts the manager to warn him of a possible problem." Eleven more scenarios were defined with reactions to different situations both in the control room, such as a detection and alarm from a sensor, or on field, such as the presence of a strong wind. These twelve scenarios were validated by an ex-control room operator with experience in training activities.

From these twelve design scenarios, situation parameters were defined and a set of five scenarios was defined and performed during testing. Each of the defined scenarios were used to simulate different situations and operators' reactions.

The first scenario (low-risk situation with detection confirmation) is a low-risk leak situation with validation from multiple sensor detection. It represents most situations operators have been confronted with.

The second scenario (low-risk situation without confirmation) aims at providing the operator with an alarm that will not be validated through multiple sources to push information requests. It is expected that the operator will need more information to validate that there is a leak in the process, but will still order evacuation of staff working on site.

Table 1- List of the identified reality anchors



Reality anchors	Type	Multiplicity
Alarm audio signal	Alarms signal	Unique
Alarm visual signal	Alarms signal	Unique
Number of alarms	Alarms signal	Unique
Gas leak position	Gas leak technical characteristics	Unique
Gas leak flow rate	Gas leak technical characteristics	Unique
Gas leak detection time	Gas leak technical characteristics	Unique
Gas leak nature	Gas leak technical characteristics	Unique
Gas leak sound	Gas leak technical characteristics	Unique
Gas leak smell	Gas leak technical characteristics	Unique
Gas leak vapors	Gas leak technical characteristics	Unique
Sensor name	Sensor	Multiple
Sensor type	Sensor	Multiple
Sensor status	Sensor	Multiple
Sensor position	Sensor	Multiple
Permit name	Permit characteristics	Multiple
Permit position	Permit characteristics	Multiple
Permit date	Permit characteristics	Multiple
Permit type	Permit characteristics	Multiple
People involved in the permit	Permit characteristics	Multiple
Weather wind direction	Weather	Unique
Weather wind speed	Weather	Unique
CCTV visual feed	CCTV	Multiple
CCTV IR images	CCTV	Multiple
Site layout map	Layout	Multiple
Impacted equipment	Process characteristics	Multiple
Equipment position	Process characteristics	Multiple
Equipment pressure	Process characteristics	Multiple
Control valve opening value	Process characteristics	Multiple
Control valve setpoint	Process characteristics	Multiple
KPI trends	Process characteristics	Multiple
Process layout	Layout	Multiple

The third scenario (repetitive detection without confirmation) represents the sensors' defection with an intermittent alarm, either a false alarm or a very minor gas leak. It is expected that the operator will need more information to validate the fact that there is a leak in the process.

The fourth scenario (high-risk situation with multiple detection) is a high-risk scenario with multiple sensors detection, people, high flammability risk due to the nature of the work performed and a static wind that encourages large gas cloud formation. It is expected that the operator will shut down the process and order evacuation of staff on site.

The fifth scenario (medium risk situation with late confirmation) aims at providing sensor validation later in the scenario to see the impact of validation on the operator's choice. It is expected that the operator will ask for staff evacuation before the second alarm starts.

These scenarios were validated by the same expert operator as for the design scenarios.

According to the scenario's definition, the prototype is implemented. The goal is to implement every RA defined in the previous steps into a DT prototype. For safety reasons, modifying a control room on an operating FPSO was not possible. Implementation of a DT simulation was therefore chosen. However, working with a simulation also provided greater flexibility for the prototype's implementation. This prototype is called a

Camara Dit Pinto, S., E. Villeneuve, D. Masson, G.A. Boy, and L. Urfels, 2024. Reality Anchor Methodology: How to Design a Digital Twin to Support Situation Awareness, Journal of Engineering Design, 1–25. https://doi.org/10.1080/09544828.2024.2336838

simulation as it aims to represent a real-time DM support DT but is not linked to a physical twin. Indeed, it simulates data as if it was coming from a real FPSO. However, using a simulation created limitations for the RA representation in the prototype and three RAs could not be implemented: (1) Closed-Circuit Television (CCTV) images were replaced with static images of the site, (2) Infra-Red (IR) images were not implemented and (3) process Key Performance Indicator (KPI) trends could not be implemented either. Apart from these three reality anchors, all other RAs were implemented in the prototype.

This study aims to improve SA based on data implemented in the DT. Therefore, no study was conducted on the UI organisation. However, to ensure that the implemented UI does not negatively impact user performance, the UI was designed based on UX design requirements and iteratively refined with an oil-and-gas operator. A company specialised in UX design counselling, performed UX testing based on previous control room UI design to generate preliminary recommendations for future UI implementation. The recommendations were implemented in the UI.

To implement the Wizard of Oz principle, the prototype was designed as an online two-player game using UNITY software[1]. Both players have the same interfaces, one for process information and the other for context information. However, the Wizard of Oz has the ability to change the values in the process interface and to start fictive gas leak effects in the control room.

As for previous steps, the prototype's implementation and realism were validated with a domain expert. During validation, comments related to UI and the colour used, the icons selected, the process value evolution rate and even the alarm system's behaviour were tackled to ensure a realistic UX throughout the tests.

User testing

The test protocol enabled how the user testing phase will be conducted to be defined (Figure 9). This was the first step to build the base of testing and ensure the validity of the evaluation. The protocol defined the choice of the training phase to allow the user to become familiar with the prototype. In this use case, the choice was made to define five scenarios to immerse the operator in different realistic situations. As part of this protocol, the evaluation techniques used to evaluate the prototype's impact were also defined.

Five operators, considered experts (with more than 15 years' experience in the field), took part in the tests. These operators were considered as commodity sampling due to the difficulty to access such profiles.

The training phase aims to familiarise the user with the prototype. For this use case, the choice was made to present a checklist to ensure the user had time to explore the tool. This phase aimed to identify missing elements and implement user needs in the DT. The defined checklist was divided into three sections that focused on the two UI (one for the process and one for the context) and on the link between them. To ensure learning, the user was asked about every type of interaction with the prototype using a checklist. These actions ensured the user would be shown how to access information, as well as where and which information was accessible. Regarding the process UI, the user was asked about actions, like 'Show PV20021A valve details' or 'Close SDV20061 valve'. Regarding the

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[1] https://unity.com/

context UI, the user was asked about similar actions such as ‘Select section S7 on the site map’ or ‘Show list of permits’. Regarding the interaction between the two interfaces, the operator was asked to identify the same elements on the two interfaces to ensure the link between the process and the site layouts has been correctly understood.

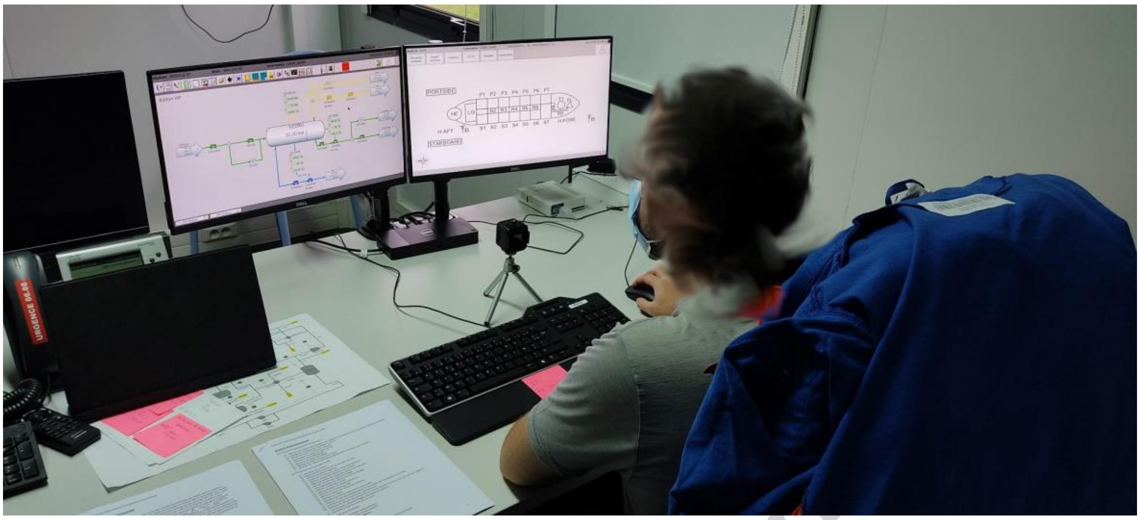
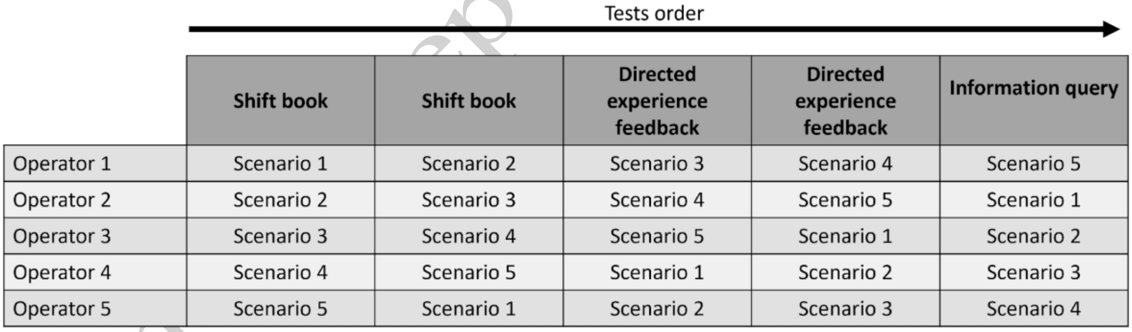


Figure 9 - Tests being performed on the prototype in a fictive control room

Once the checklist was completed and the operator's questions answered, the operator was considered to be familiar with the UI and the tests were presented to the operator. At the end of each scenario, the operator was asked to fill out an experience feedback form. Three types of forms were presented, a free-expression form, a directed form and a query-based form. These scenarios and corresponding forms were proposed in a specific order (cf. Figure 10).



Tests order

	Shift book	Shift book	Directed experience feedback	Directed experience feedback	Information query
Operator 1	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Operator 2	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 1
Operator 3	Scenario 3	Scenario 4	Scenario 5	Scenario 1	Scenario 2
Operator 4	Scenario 4	Scenario 5	Scenario 1	Scenario 2	Scenario 3
Operator 5	Scenario 5	Scenario 1	Scenario 2	Scenario 3	Scenario 4

Figure 10 - Scenario and experience feedback order

This scenario order ensured the rotation of the couple scenario/feedback type and ensured two shift book type forms and two directed type forms for each scenario. As the query type form is highly descriptive and would bias the operator memorising information, it was decided to only recover one such form type for each scenario and that was always the last one to be used.

Results

To collect results from the testers, the protocol defined previously was used with the implemented prototype. Three sources of results were analysed:

(1) SART results provide insight into the effect of the prototype on the user SA through the DT's ability to provide access to RAs for each scenario.
(2) Experience feedback results enable RAs used by operators to be identified in order to describe a situation with different levels of detail.
(3) Activity analysis allows the process used by operators to access information in the tool to be identified when confronted with the need to assess a situation.

Situation awareness evaluation

The use of the SART aimed to identify the ability of the operators to perceive situation complexity and keep attention on both interfaces. It also aimed to identify possible cognitive overload and assess the realism of the scenarios used.

To enable analysis and comparisons, the results of the SART were implemented into radar charts which provide a comprehensive evaluation (W.A.N.G. et al. 2017). These figures represent operator ratings related to a specific scenario.

Figure 11 shows an example of the chart obtained for the first scenario.

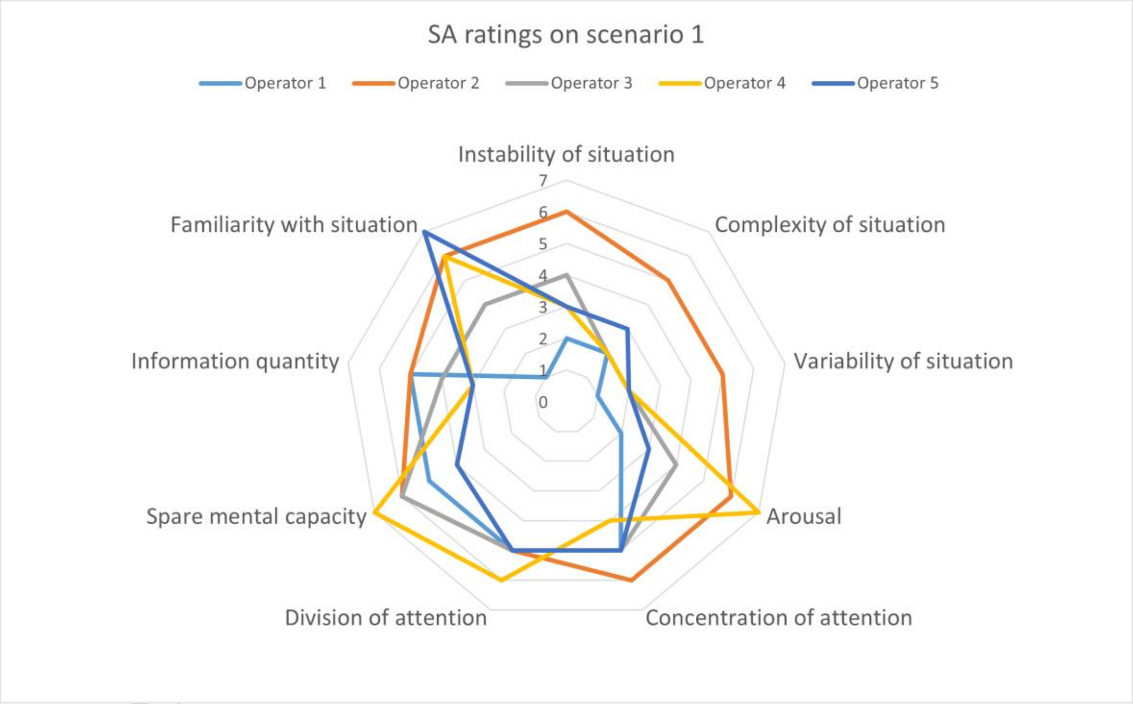


Figure 11 - Example of SART radar chart result for the first scenario

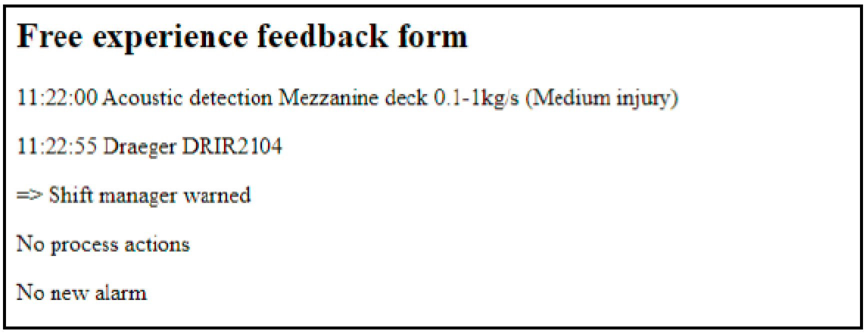
The synthesis of the results for all the tests carried out (for all operators and all scenarios) shows that the operators shared their attention evenly across the information. Supporting this ability is therefore important. Regarding familiarity with the situation, it was expected to be higher for each scenario as it was extracted from past real situations expressed by operators. It seems that the use of new sensors and the use of a new operational site led operators to lower their rating in this category. It shows the importance for operators of being familiar with the site's configuration and not only with the developing situation. Regarding the quantity of information and spare mental capacity, usual information can be used to support operators while avoiding mental overload. This validates the fact that the tool can be used in a real situation to support users without exceeding their decision-making capacity. Regarding the evaluation of the situation in general, no common ratings were found. However, it can be said that higher ratings regarding instability, complexity and variability appeared when having to deal with a fast-evolving risky situation involving human safety.

Experience feedbacks

To analyse the results of the feedback forms, tables, containing the number of occurrences of each reality anchor-based concept, were defined for each scenario. These tables show three major types of results. First, the concepts that were used in the directed forms. Identifying those concepts shows reality anchors that are added as details of the situation. Then, the concepts that were used in the free forms only. Identifying those concepts shows reality anchors that disappear with a higher level of detail. This can be explained by the use of different concepts or elements that are specific to a short description of the situation. And finally, the concepts that were not used in any experience feedback forms. Identifying those concepts shows a lower priority in terms of usage in the description of a situation.

For example, in the first scenario (see Figure 12), we can see that the first line refers to an alarm from an acoustic sensor. The operator also references the time which refers to the date of the event. In addition, it can be said that the word “acoustic” refers to the type of sensor, the ‘Mezzanine deck’ refers to the leak position, the ‘0.1-1kg/s’ refers to the leak flow rate, and the ‘(Medium injury)’ refers to the severity of the leak.

Applying the same exercise to the next lines other concepts can be identified like: (1) an alarm from a Dräger sensor (gas concentration detector), (2) the date, (3) the sensor type, (4) and the sensor name.



Free experience feedback form

11:22:00 Acoustic detection Mezzanine deck 0.1-1kg/s (Medium injury)

11:22:55 Draeger DRIR2104

=> Shift manager warned

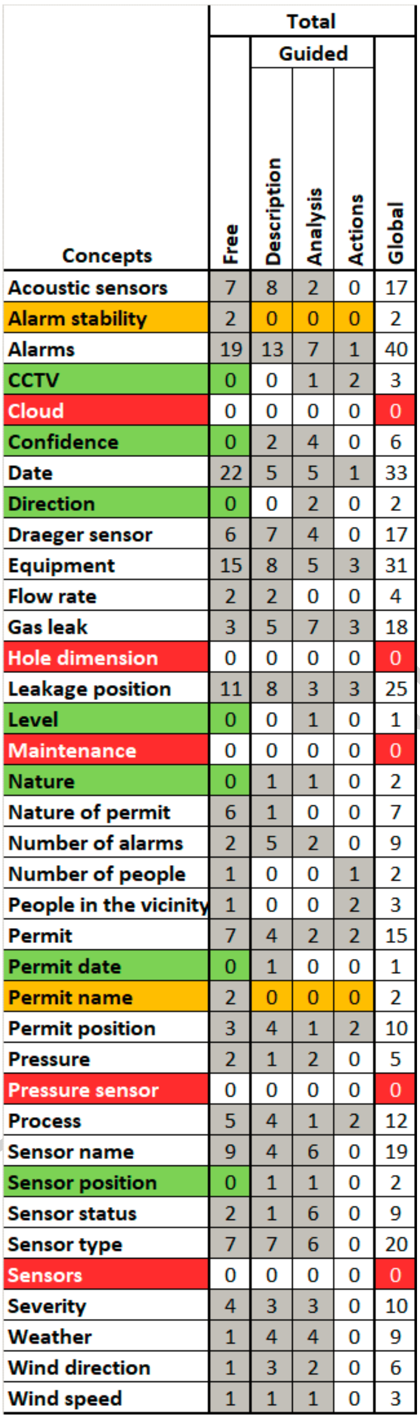
No process actions

No new alarm

Figure 12 - Example of Experience feedback form coming from the first scenario

Regarding the query-based form, it was used to validate the fact that the user had knowledge about how to access information in the tool.

The results from every experience feedback form were compiled and shaped into one table that show the general use of RAs by the operators (see Figure 13). In those tables, we identified in white the anchors used for both guided or free description, in green the reality anchors used only in guided more detailed description, in orange the anchors used only for general free description and in red those not used by any operator.



Concepts	Total				
	Free	Guided			Global
		Description	Analysis	Actions	
Acoustic sensors	7	8	2	0	17
Alarm stability	2	0	0	0	2
Alarms	19	13	7	1	40
CCTV	0	0	1	2	3
Cloud	0	0	0	0	0
Confidence	0	2	4	0	6
Date	22	5	5	1	33
Direction	0	0	2	0	2
Draeger sensor	6	7	4	0	17
Equipment	15	8	5	3	31
Flow rate	2	2	0	0	4
Gas leak	3	5	7	3	18
Hole dimension	0	0	0	0	0
Leakage position	11	8	3	3	25
Level	0	0	1	0	1
Maintenance	0	0	0	0	0
Nature	0	1	1	0	2
Nature of permit	6	1	0	0	7
Number of alarms	2	5	2	0	9
Number of people	1	0	0	1	2
People in the vicinity	1	0	0	2	3
Permit	7	4	2	2	15
Permit date	0	1	0	0	1
Permit name	2	0	0	0	2
Permit position	3	4	1	2	10
Pressure	2	1	2	0	5
Pressure sensor	0	0	0	0	0
Process	5	4	1	2	12
Sensor name	9	4	6	0	19
Sensor position	0	1	1	0	2
Sensor status	2	1	6	0	9
Sensor type	7	7	6	0	20
Sensors	0	0	0	0	0
Severity	4	3	3	0	10
Weather	1	4	4	0	9
Wind direction	1	3	2	0	6
Wind speed	1	1	1	0	3

Figure 13 - Compiled results from the experience feedback analysis

The results from the experience feedback forms showed the importance of the concept linked to the alarm detection system in the description of the situation. It also showed that these concepts are used by operators to perceive the situation and focus on the information to be acquired in greater detail. The secondary information is identified as linked to the concepts of the impacted equipment and people in the vicinity.

These results also validate the RAs identified in the elicitation step and their use in the acquisition of SA. Indeed, there were no elements that were not in the RA list that had been used to describe the situation.

As for the RAs that were not used in the forms, three types of RAs can be observed: (1) concepts that are not usually used by operators, like maintenance, (2) concepts that relate to a gas leak but cannot be easily identified, like the size of a hole or the position of a gas cloud and (3) concepts that are part of the process and not considered specifically, like the pressure sensors.

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Activity analysis

In this experiment, the recording of the two screens was performed using a camera pointed at both. This method combines recording the user's voice for the think-out-loud technique (Olson, Duffy, and Mack 2018) and recording the movements of the pointer on the screen.

The resulting recordings were analysed using The Observer XT[2]. This software enables events and states to be tagged on the video timeline to extract a stamp-timed list of activities. The recorded activities and states were then converted into a status of availability on screen for every RA. An analysis of every anchor availability is performed by defining the availability ratio of the anchor for each user and for each scenario to draw conclusions on their role in the decision-making process (see Figure 14). Looking at the results, it is possible to draw some general conclusions regarding the availability of the RAs. Regarding the sensors, detailed information like the name of the sensor is very rarely used by the users while making a decision. However, other related information that is available while being on the map where the detection occurred shows a high ratio of availability which means that the user spends most of their time on the context interface where that information is available. This result is validated by the fact that operators spend at least 50% of their actions having the leakage point available to them.

Other leak detection related RAs (that have to be accessed) were available to the user at least once and even show more than 20% availability for some users. This highlights the importance of these RAs.

RAs related to permit-to-work are available at least once for most users even when no permit is currently being performed on-site. This shows the importance of these RAs.

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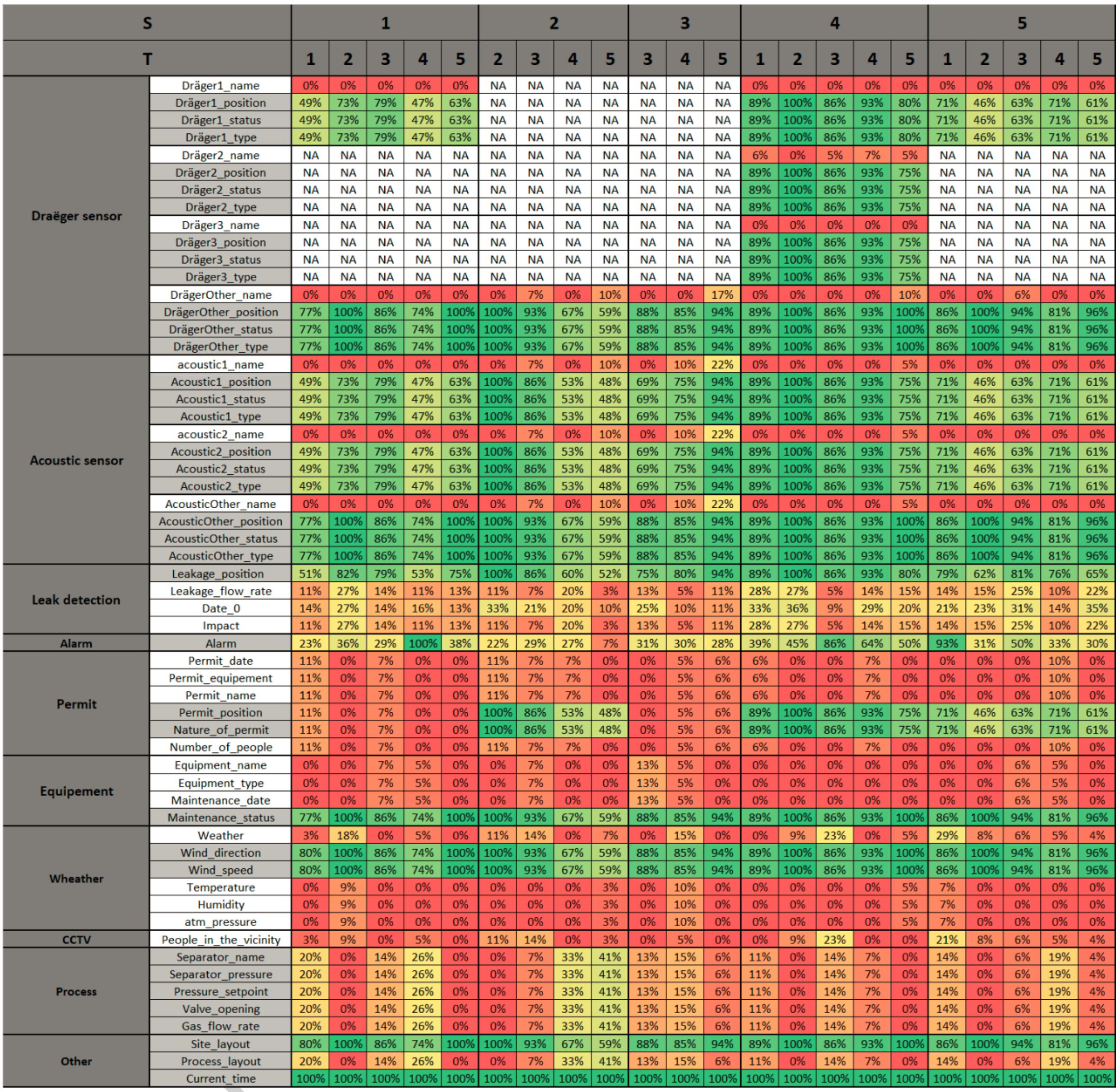
[2] The Observer XT is a behaviour analysis software package: www.noldus.com/observer-xt}

Recommendations could include making the number of permits currently performed on-site constantly available to the user. This will enable users to know if they need to access more information or not.



S		1					2				3			4					5				
T		1	2	3	4	5	2	3	4	5	3	4	5	1	2	3	4	5	1	2	3	4	5
Draëger sensor	Dräger1_name	0%	0%	0%	0%	0%	NA	NA	NA	NA	NA	NA	NA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Dräger1_position	49%	73%	79%	47%	63%	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	80%	71%	46%	63%	71%	61%
	Dräger1_status	49%	73%	79%	47%	63%	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	80%	71%	46%	63%	71%	61%
	Dräger1_type	49%	73%	79%	47%	63%	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	80%	71%	46%	63%	71%	61%
	Dräger2_name	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	6%	0%	5%	7%	5%	NA	NA	NA	NA	NA
	Dräger2_position	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	75%	NA	NA	NA	NA	NA
	Dräger2_status	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	75%	NA	NA	NA	NA	NA
	Dräger2_type	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	75%	NA	NA	NA	NA	NA
	Dräger3_name	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0%	0%	0%	0%	0%	NA	NA	NA	NA	NA
	Dräger3_position	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	75%	NA	NA	NA	NA	NA
	Dräger3_status	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	75%	NA	NA	NA	NA	NA
	Dräger3_type	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	89%	100%	86%	93%	75%	NA	NA	NA	NA	NA
	DrägerOther_name	0%	0%	0%	0%	0%	0%	7%	0%	10%	0%	0%	17%	0%	0%	0%	0%	10%	0%	0%	6%	0%	0%
	DrägerOther_position	77%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
	DrägerOther_status	77%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
	DrägerOther_type	77%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
Acoustic sensor	acoustic1_name	0%	0%	0%	0%	0%	0%	7%	0%	10%	0%	10%	22%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%
	Acoustic1_position	49%	73%	79%	47%	63%	100%	86%	53%	48%	69%	75%	94%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	Acoustic1_status	49%	73%	79%	47%	63%	100%	86%	53%	48%	69%	75%	94%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	Acoustic1_type	49%	73%	79%	47%	63%	100%	86%	53%	48%	69%	75%	94%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	acoustic2_name	0%	0%	0%	0%	0%	0%	7%	0%	10%	0%	10%	22%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%
	Acoustic2_position	49%	73%	79%	47%	63%	100%	86%	53%	48%	69%	75%	94%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	Acoustic2_status	49%	73%	79%	47%	63%	100%	86%	53%	48%	69%	75%	94%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	Acoustic2_type	49%	73%	79%	47%	63%	100%	86%	53%	48%	69%	75%	94%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	AcousticOther_name	0%	0%	0%	0%	0%	0%	7%	0%	10%	0%	10%	22%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%
	AcousticOther_position	77%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
	AcousticOther_status	77%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
	AcousticOther_type	77%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
Leak detection	Leakage_position	51%	82%	79%	53%	75%	100%	86%	60%	52%	75%	80%	94%	89%	100%	86%	93%	80%	79%	62%	81%	76%	65%
	Leakage_flow_rate	11%	27%	14%	11%	13%	11%	7%	20%	3%	13%	5%	11%	28%	27%	5%	14%	15%	14%	15%	25%	10%	22%
	Date_0	14%	27%	14%	16%	13%	33%	21%	20%	10%	25%	10%	11%	33%	36%	9%	29%	20%	21%	23%	31%	14%	35%
	Impact	11%	27%	14%	11%	13%	11%	7%	20%	3%	13%	5%	11%	28%	27%	5%	14%	15%	14%	15%	25%	10%	22%
Alarm	Alarm	23%	36%	29%	100%	38%	22%	29%	27%	7%	31%	30%	28%	39%	45%	86%	64%	50%	93%	31%	50%	33%	30%
Permit	Permit_date	11%	0%	7%	0%	0%	11%	7%	7%	0%	0%	5%	6%	6%	0%	0%	7%	0%	0%	0%	0%	10%	0%
	Permit_equipement	11%	0%	7%	0%	0%	11%	7%	7%	0%	0%	5%	6%	6%	0%	0%	7%	0%	0%	0%	0%	10%	0%
	Permit_name	11%	0%	7%	0%	0%	11%	7%	7%	0%	0%	5%	6%	6%	0%	0%	7%	0%	0%	0%	0%	10%	0%
	Permit_position	11%	0%	7%	0%	0%	100%	86%	53%	48%	0%	5%	6%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	Nature_of_permit	11%	0%	7%	0%	0%	100%	86%	53%	48%	0%	5%	6%	89%	100%	86%	93%	75%	71%	46%	63%	71%	61%
	Number_of_people	11%	0%	7%	0%	0%	11%	7%	7%	0%	0%	5%	6%	6%	0%	0%	7%	0%	0%	0%	0%	10%	0%
Equipement	Equipment_name	0%	0%	7%	5%	0%	0%	7%	0%	0%	13%	5%	0%	0%	0%	0%	0%	0%	0%	0%	6%	5%	0%
	Equipment_type	0%	0%	7%	5%	0%	0%	7%	0%	0%	13%	5%	0%	0%	0%	0%	0%	0%	0%	0%	6%	5%	0%
	Maintenance_date	0%	0%	7%	5%	0%	0%	7%	0%	0%	13%	5%	0%	0%	0%	0%	0%	0%	0%	0%	6%	5%	0%
	Maintenance_status	77%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
Wheather	Weather	3%	18%	0%	5%	0%	11%	14%	0%	7%	0%	15%	0%	0%	9%	23%	0%	5%	29%	8%	6%	5%	4%
	Wind_direction	80%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
	Wind_speed	80%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
	Temperature	0%	9%	0%	0%	0%	0%	0%	0%	3%	0%	10%	0%	0%	0%	0%	0%	5%	7%	0%	0%	0%	0%
	Humidity	0%	9%	0%	0%	0%	0%	0%	0%	3%	0%	10%	0%	0%	0%	0%	0%	5%	7%	0%	0%	0%	0%
	atm_pressure	0%	9%	0%	0%	0%	0%	0%	0%	3%	0%	10%	0%	0%	0%	0%	0%	5%	7%	0%	0%	0%	0%
CCTV	People_in_the_vicinity	3%	9%	0%	5%	0%	11%	14%	0%	3%	0%	5%	0%	0%	9%	23%	0%	0%	21%	8%	6%	5%	4%
Process	Separator_name	20%	0%	14%	26%	0%	0%	7%	33%	41%	13%	15%	6%	11%	0%	14%	7%	0%	14%	0%	6%	19%	4%
	Separator_pressure	20%	0%	14%	26%	0%	0%	7%	33%	41%	13%	15%	6%	11%	0%	14%	7%	0%	14%	0%	6%	19%	4%
	Pressure_setpoint	20%	0%	14%	26%	0%	0%	7%	33%	41%	13%	15%	6%	11%	0%	14%	7%	0%	14%	0%	6%	19%	4%
	Valve_opening	20%	0%	14%	26%	0%	0%	7%	33%	41%	13%	15%	6%	11%	0%	14%	7%	0%	14%	0%	6%	19%	4%
	Gas_flow_rate	20%	0%	14%	26%	0%	0%	7%	33%	41%	13%	15%	6%	11%	0%	14%	7%	0%	14%	0%	6%	19%	4%
Other	Site_layout	80%	100%	86%	74%	100%	100%	93%	67%	59%	88%	85%	94%	89%	100%	86%	93%	100%	86%	100%	94%	81%	96%
	Process_layout	20%	0%	14%	26%	0%	0%	7%	33%	41%	13%	15%	6%	11%	0%	14%	7%	0%	14%	0%	6%	19%	4%
	Current_time	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 14 - Results of the availability ratio of the reality anchors during the scenarios

RAs related to the equipment show a low ratio of availability. These results show that not much interest is given to the details of equipment and maintenance on the context interface. This information might be discarded if needed.

Looking at the weather information, multiple detailed information was made accessible to the user (temperature, pressure, humidity). However, looking at the results, few operators had these available while making their decision. This shows that, as for the maintenance RAs, these could be discarded if necessary.

CCTV RA was simulated and therefore not realistic enough to decide in the situation. However, users were asked to access that information nonetheless if they wished to have it available. The results show that users accessed this information, and that this RA needs to be kept.

Finally, the ratio of availability of the process related RAs shows the importance of the tool to maintain a direct link with those RAs.

Discussion and perspectives

In conclusion, the absence of human-centred methodologies for DT design was fulfilled by the definition of RAM. This methodology was aimed at proposing a detailed process for DT implementation through eliciting, implementing and validating the RAs in a DT prototype.

The application of the methodology to the use case provided results to work with but showed limitations. These limitations lie in the uncertainty that accompanies testing with humans and the medium used to record results. Working with experts means having access to them. The specificity of the control room operating environment, where operators are required to be fully focused, means they are unavailable to spend too much time with them. As a result, the panel of testers was limited, and the time required to complete five tests was substantial.

Regarding the tools used to capture the results, the absence of an eye-tracking device forced us to work on the availability of the RAs and not their perception by the user. The results, therefore, depend on a major assumption that the tester used the RAs made available. The results give a picture of the reality anchors used but do not directly reflect the activity performed by the user. This is especially true for information that is contextualised on maps and thus almost constantly available to the user. The solution would be to use systems that record the user’s vision and points of interest or by implementing the system in a way that forces the user to access the information. However, devices for eye tracking were not available at the time of this study and modifying the prototype interface would have had counterintuitive results and would not have yielded results for its improvement.

Apart from these limitations, the results obtained in this study showed the impact of the tool on situation awareness and gave insight into how to improve the prototype to develop a tool that satisfies the user's needs. This methodology was used for DT implementation. However, most systems currently developed are closer to the Digital Shadow paradigm. Therefore, it would be interesting to see how this methodology can be applied to such systems that do not have an automated link between the physical system and its digital counterpart.

Acknowledgement

This research project was undertaken with the assistance of resources and services of TotalEnergies (https://totalenergies.com/).

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