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Reality Anchor Methodology : Designing a digital twin supporting situation awareness

Stélian Camara Dit Pinto

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Reality Anchor Methodology: Designing a digital twin supporting situation awareness

Méthode des ancres de la réalité :

Comment concevoir un jumeau numérique pour supporter la conscience de la situation ?

Thèse de doctorat de l'université Paris-Saclay

École doctorale n°573 : interfaces : matériaux, systèmes, usages (INTERFACES)

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Graduate School : Science de l'ingénierie et des systèmes Référent : CentraleSupélec

Thèse préparée dans les unités de recherche **Université Paris-Saclay, CentraleSupélec, Laboratoire Génie Industriel** et **UNIV. BORDEAUX, ESTIA INSTITUTE OF TECHNOLOGY**, sous la direction de **Guy André BOY**, Pr., le co-encadrement de **Dimitri MASSON**, PhD, le co-encadrement de **Éric VILLENEUVE**, PhD et de la représentation technique de **Laetitia URFELS**, PhD

Thèse soutenue à Paris-Saclay, le 26 septembre 2022, par

Stélian CAMARA DIT PINTO

Composition du Jury

Marija JANKOVIC

Pr., Université Paris-Saclay,
CentraleSupélec, LGI

Présidente du jury

Marie-Pierre PACAUX-LEMOINE

IR, HDR, Université Polytechnique
Haut de France, LAMIH (UMR
CNRS 8201)

Rapporteur & Examinatrice

Hind BRIL EL HAOUZI

Pr., Université de Lorraine, ENSTIB,
CRAN (UMR CNRS 7039)

Rapporteur & Examinatrice

Guy André BOY

Pr., Université Paris-Saclay,
CentraleSupélec, LGI and UNIV.
BORDEAUX, ESTIA INSTITUTE OF
TECHNOLOGY

Directeur de thèse

Titre : Méthode des ancrés de la réalité : Comment concevoir un jumeau numérique pour supporter la conscience de la situation ?

Mots clés : Intégration Humains Systèmes, Jumeau numérique, Conscience de la situation, Méthodologie de conception, Systèmes complexes

Résumé : L'industrie 4.0 permet l'optimisation des systèmes complexes par la digitalisation et donc l'acquisition de nouvelles données. Ces nouvelles données, si elles doivent permettre d'améliorer la prise de décision, génèrent également une complexité supplémentaire pour les opérateurs humains qui y sont confrontés. En étudiant le phénomène de la prise de décision humaine, le concept de conscience de la situation apparaît comme primordial face à ces systèmes complexes.

Pour soutenir la prise de décision, des outils appelés systèmes d'aide à la prise de décision ont été développés. L'importance du rôle de la conscience de la situation dans la prise de décision a engendré une spécialisation de ces systèmes sous la forme de Systèmes de Soutien à la Conscience de la Situation (SSCS). Les travaux présentés dans cette thèse s'intéressent à l'opportunité d'utiliser le Jumeau Numérique (JN) du système complexe, concept popularisé ces dernières années dans le cadre des travaux scientifiques autour de l'industrie 4.0, pour en faire un SSCS. Ainsi après avoir proposé une nouvelle définition du concept de JN, basé sur une étude de la littérature scientifique, une étude des composants de ce type de système en relation avec la notion de conscience de la situation a été menée pour en extraire des spécifications de conception.

Ensuite, une exploration de la littérature scientifique concernant conjointement la conception des SSCS et les méthodes de conception centrée utilisateur associées a permis de mettre en évidence la nécessité de transmettre des éléments contextuels de la situation à l'utilisateur pour améliorer sa conscience de la situation et donc l'assister dans sa prise de décision.

Etant donné (1) la complexité du système à représenter dans le JN et donc la complexité du JN en lui-même et (2) la nécessité d'immerger l'utilisateur pour permettre l'acquisition de la conscience de la situation au travers d'un SSCS, le concept d'ancres de la réalité est proposé pour identifier les éléments de la situation nécessaire à l'utilisateur pour percevoir, comprendre et projeter la situation à laquelle il fait face. Une méthode, appelée Méthode des Ancres de la Réalité, a été définie pour assurer l'implémentation de ces éléments dans un SSCS.

Cette méthode est composée de trois étapes qui visent (1) à définir les ancrés de la réalité au travers d'une étude des tâches et des activités des opérateurs, (2) à créer un prototype pour la réalisation de test humain-dans-la-boucle et (3) à valider la définition des ancrés de la réalité au travers d'une analyse de la conscience de la situation, des retours d'expérience et des activités réalisées lors des tests.

Cette méthode a été appliquée sur un cas d'étude du domaine des activités de TotalEnergies et a validé l'importance des ancrés de la réalité définies pour le processus de prise de décision.

Title: Reality Anchor Methodology: how to design a digital twin supporting situation awareness?

Keywords: Human Systems Integration, Digital twin, Situation awareness, Design methodology, Complex systems

Abstract: Industry 4.0 allows the optimization of complex systems through digitalization and therefore the acquisition of new data. This new data, while it should improve decision making, also generates additional complexity for human operators who are confronted with it. In studying the phenomenon of human decision making, the concept of situational awareness appears to be of primary importance when dealing with these complex systems.

To support decision making, tools called decision support systems have been developed. The importance of the role of situational awareness in decision making has led to a specialization of these systems in the form of Situation Awareness Support Systems (SASS). The work presented in this dissertation focuses on the opportunity to use the Digital Twin (DT) of the complex system, a concept popularized in recent years in the context of scientific work around Industry 4.0, to make it a SASS.

Thus, after proposing a new definition of the concept of JN, based on a study of the scientific literature, a study of the components of this type of system in relation to the notion of situational awareness was conducted to extract design specifications.

Then, an exploration of the scientific literature concerning jointly the design of SASS and the associated user-centered design methods allowed to highlight the necessity to transmit contextual elements of the situation to the user to improve his situational awareness and thus assist him in his decision making.

Given (1) the complexity of the system to be represented in the DT and thus the complexity of the DT itself and (2) the need to imitate the user to allow the acquisition of situational awareness through a SASS, the concept of reality anchor is proposed to identify the situational elements necessary for the user to perceive, understand and project the situation he is facing. A method, called the Reality Anchor Methodology (RAM), has been defined to ensure the implementation of these elements in a SASS.

This method is composed of three steps that aim (1) to define the reality anchors through a study of the operators' tasks and activities, (2) to create a prototype for the realization of human-in-the-loop tests and (3) to validate the definition of the reality anchors through an analysis of the situational awareness, the feedbacks and the activities performed during the tests.

This method was applied to a case study in the oil industry and validated the importance of the defined reality anchors for the decision-making process

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Acronyms

AI	Artificial Intelligence	IDSS	Intelligent Decision Support System
BDV	Blow Down Valve	INCOSE	International Council on Systems Engineering
BPMN	Business Process Modeling Notation	IoT	Internet Internet of Thing
CaDSS	Context-aware Decision Support Systems	ISAS	Intelligent SA systems
CCTV	Close-Circuit TeleVision	KBB	Knowledge-based behavior
CDM	Critical Decision Method	KPI	Key Performance Indicator
CFA	Cognitive Function Analysis	LV	Level Valve
CPS	Cyber-Physical Systems	PLM	Product Lifecycle Management
DQT	Direct Questioning Technique	PN	Propositional Network
DSA	Distributed Situation Awareness	PV	Pressure Valve
DSS	Decision Support Systems	RA	Reality Anchors
EID	Ecological Interface Design	RAM	Reality Anchor Methodology
EP	Exploration and Production	RBB	Rule-based behavior
ESDV	Emergency Shut Down Valve	REX	Return of Experience
FPSO	Floating Production Storage and Offloading facility	RST	Rough Set Theory
GDTA	Goal-Directed Task Analysis	SA	Situation Awareness
HCD	Human-Centered Design	SACRI	Situation Awareness Control Room Inventory
HCI	Human Computer Interaction	SAGAT	Situation Awareness Global Assessment Technique
HSE	Health Safety Environment, 23		

SAOD
Situation Awareness Oriented Design
SART
Situation Awareness Rating
Technique
SASS
Situation Awareness Support System
SBB
Skill-based behavior

SDV
Shut Down Valve
SE
Systems Engineering
SRK
Skills, Rules, Knowledge
UX
User eXperience

Résumé étendu

Les sites pétroliers sont des systèmes complexes étant donnés les multiples équipements qui les composent, les interactions entre ces composants, ainsi que la présence d'humains interagissant avec le système. Cette thèse se focalise sur la nécessité d'assister l'entreprise TotalEnergies dans la conception d'un jumeau numérique pour aider les consolistes (opérateurs en salle de contrôle du procédé industriel) dans la gestion des situations dégradées via une aide à la prise de décision en temps réel pendant la production. Dans cette optique, ces travaux s'inscrivent dans le domaine de l'Intégration Humains Système qui se situe à l'intersection entre l'ingénierie des systèmes et la conception centrée utilisateur. Dans le cadre de ces travaux, je me suis rapproché et ai participé aux réflexions du Groupe de Travail « Human System Integration » (HSI) de l'INCOSE. En particulier lors de la rédaction de la section sur la définition des activités orienté HSI dans le cycle de vie d'un système du Primer HSI (à paraître). Dans le cadre du cycle de vie du système, cette thèse se focalise en particulier dans les phases de conception et de développement d'un système complexe.

Dans le cadre de la phase de conception, un état de l'art sur le concept de jumeau numérique a permis d'identifier les définitions et rôles pour ces systèmes. Cependant, aucune définition ne prend en compte les capacités complètes d'un tel système ainsi que la dimension humaine de l'interaction entre le système et un décideur. Une première contribution de cette thèse repose donc sur la proposition d'une définition prenant en compte ces aspects¹. Ainsi, le jumeau numérique a été défini comme *une représentation dynamique d'un système physique utilisant les données, modèles et processus interconnectés donnant accès à des connaissances issues des états passés, présents et futurs pour la gestion du système*. Pour accompagner cette définition conceptuelle, une définition opérationnelle sous forme de composants a également été proposée. Cette définition implémente six composants issus des multiples définitions et implémentations de la littérature pour définir un jumeau numérique complet. Pour compléter cette contribution fondamentale sur le concept de jumeau numérique, un état de l'art sur le phénomène de prise de décision a été mené et a permis d'identifier l'importance du concept de conscience de la situation, notamment dans sa déclinaison dite « partagée » telle que définie par Stanton². Cette vision de la conscience de la situation transpose les étapes de perception, compréhension et

¹ Camara Dit Pinto Stélian, Éric Villeneuve, Dimitri Masson, Guy André Boy, Thierry Baron, and Laetitia Urfels. 2021. "Digital Twin Design Requirements in Downgraded Situations Management." in Incom 2021 proceedings.

² Stanton, N. A., R. Stewart, D. Harris, R. J. Houghton, C. Baber, R. McMaster, P. Salmon, G. Hoyle, G. Walker, M. S. Young, M. Linsell, R. Dymott, and D. Green. 2006. "Distributed Situation Awareness in Dynamic Systems: Theoretical Development and Application of an Ergonomics Methodology." *Ergonomics* 49(12-13):1288-1311.

projection (définie par Endsley³) aux systèmes et s'intéresse au partage de la conscience de la situation entre les humains et les systèmes.

Dans ce contexte, la problématique de recherche qui a été étudiée dans cette thèse est la suivante : Comment concevoir un système de soutien à la conscience de la situation pour aider à la prise de décision en temps réel en situation anormale ?

En étudiant le phénomène d'acquisition de la conscience de la situation chez les décideurs, il est apparu que, dans le cadre de l'immersion de l'humain dans la situation, l'acquisition des éléments de la réalité au travers des sens est directe. Cependant, dans le cadre de l'utilisation d'outils de gestion numériques, composés de modèles de la situation, il est important d'apporter à l'utilisateur, au travers de ces modèles, les éléments de la réalité aussi proche que possible de ceux qu'il aurait acquis en direct pour lui permettre de s'ancrer dans la réalité. Ainsi, le concept d'*Ancre de la Réalité* a été défini comme *les éléments de la situation nécessaires à un humain pour s'ancrer dans la réalité et acquérir une conscience de la situation informée qui soutient le processus de prise de décision*. Ces ancres de la réalité définies ici dans le cadre de la gestion à distance, se présentent comme des éléments charnières de tous outils d'aide à la prise de décision.

Dans le cadre de la phase de développement du système, une exploration des méthodes de conceptions anthropocentrées a montré l'absence de méthode centrée sur l'activité et considérant le concept d'ancre de la réalité. Face à ce manque dans la littérature, une méthode documentée de conception anthropocentrée et orientée sur l'implémentation des ancres de la réalité appelée Reality Anchor Methodology (RAM) a été proposée. Cette méthode débute par l'élicitation des ancres de la réalité nécessaire à l'utilisateur. Cette étape commence par une étude des règles et normes de l'entreprise suivie par des entretiens semi-dirigés avec les futurs utilisateurs et conclue par une analyse des fonctions cognitives pour en extraire les ressources physiques et cognitives nécessaire à la prise de décision (c'est-à-dire les ancres de la réalité). Une fois ces ancres élicitées, elles doivent être implémentées dans un prototype pour être évaluées durant des tests humains dans la boucle. L'implémentation du prototype est réalisée de manière agile et au travers de l'adaptation de méthodes issues du domaine de l'interaction humain machines telles que la conception à base de scénarios et la technique du Magicien d'Oz. L'application de la technique du Magicien d'Oz au prototypage de systèmes complexe tel qu'un jumeau numérique ouvrent la possibilité de réaliser des tests avec les utilisateurs à faible cout d'implémentation. Un ensemble d'évaluations est défini pour qualifier la validité de l'implémentation des ancres de la réalité et l'effet du prototype sur la

³ Endsley, Mica R. 1995. "Toward a Theory of Situation Awareness in Dynamic Systems." Human Factors: The Journal of the Human Factors and Ergonomics Society 37(1):32-64.

conscience de la situation de l'utilisateur. Il est composé d'un formulaire d'évaluation de la conscience de la situation (SART), d'une analyse des retours d'expériences et d'une analyse de l'activité. Ces trois étapes permettent de définir des recommandations pour itérer sur l'implémentation du système et assurer l'implémentation des ancrés de la réalité et leurs utilisations pour assister la conscience de la situation.

Cette méthode a été appliquée à un cas d'étude directement issue du domaine d'opération de TotalEnergies. Le choix du cas d'étude a été porté sur la gestion de fuite de gaz depuis la salle de contrôle. L'application de la méthode a permis la définition des processus de prise de décision du domaine, au travers de 11 entretiens réalisés avec des opérateurs du domaine, ainsi que l'élicitation de 31 ancrés de la réalité nécessaires aux opérateurs de salle de contrôle pour acquérir une conscience de la situation informée. A la suite de cette élicitation, un prototype de jumeau numérique pour salle de contrôle a été implémenté. Cette implémentation a été réalisée sur Unity et documenté dans ses itérations sur la plateforme GitHub. Les résultats des tests utilisateur menés sur ce prototype, réalisés avec 5 opérateurs experts du domaine, ont montré la capacité du système à permettre l'acquisition d'une conscience de la situation de la part des opérateurs lors des 5 scénarios qui leur ont été présentés. L'étude de trois types de retours d'expériences (libre, dirigé et complet) a montré la bonne utilisation des ancrés de la réalité lors de la description d'une situation. L'analyse de l'activité a été réalisée par l'enregistrement des actions réalisées par les opérateurs sur le prototype et a permis d'identifier les ancrés inutilisés ou manquantes.

En conclusion, ces travaux de thèse ont permis de définir le concept de jumeau numérique tant d'un point de vue conceptuel qu'opérationnel. Ils ont également permis de définir le concept d'ancres de la réalité comme les éléments importants à modéliser dans un outil d'aide à la prise de décision pour assurer l'ancrage de l'utilisateur dans la réalité et l'acquisition d'une conscience de la situation significative. Ces travaux ont été compilés dans une méthode de conception HSI déployée sur un cas d'étude du domaine pétrolier. Lors de ce déploiement, un prototype de jumeau numérique utilisant le principe de magicien d'Oz a été implémenté et documenté pour permettre la réalisation de tests utilisateurs à faible coût.

Introduction

Since the beginning of industrialization, industrial systems have become increasingly complex. On the one hand, the challenges of increasing production have encouraged the creation of larger scale industrial sites, production lines and machines. This increase in scale has made these systems more difficult to supervise and understand. On the other hand, the miniaturization of systems has allowed for more and denser integration of these systems. While this use of multiple integrated subsystems has increased system performance, it has made them more difficult to understand and operate.

This increase in system complexity has accelerated in recent years with the digitalization of these systems. Virtual systems are quickly scaled, duplicated and customized. It has created both an increase in the complexity of these systems and the tools to manage them.

For example, the development of scientific domains like:

- Artificial Intelligence (AI) (Schuett 2019) has provided solutions to optimization problems and automated tasks that previously had to be performed by humans, but these black-box algorithms make explainability and interpretability a challenge (Zhou, Chen, and Holzinger 2022).
- Cyber-Physical Systems (CPS) have enabled new interactions between systems and humans (Baheti and Gill 2011). However, understanding the multiple interactions made available by CPS is challenging and operators have showed trust issues (Boyes 2013).
- Internet of Thing (IoT) (Patel and Keyur 2016) has connected together a multitude of systems into a network of systems. This has increased the communication ability between connected systems but has also provided challenges in terms of data management and understanding where the data is going.
- Industry 4.0 has studied the impact of new technologies to improve industrial capabilities (Brittes Benitez et al. 2019). Using CPS, IoT, AI and more, the industry 4.0 has increased productivity but made the industry more complex.

In this context of increasing complexity, Human Systems Integration (HSI) is a scientific challenge to improve the "symbiosis" between the complex system and the humans who interact with it. The consideration of these challenges has led to the definition of the principle of industry 5.0 (Zdemir and Hekim 2018), where system usability and understandability are key concepts that guided the orientation of this research work.

System usability represents how well a human operator can use the system to achieve its purpose. In fact, as the complexity of systems increases, by focusing on performance

objectives, its ability to meet user needs is usually left out. The HSI paradigm aims to address this problem and provide guidelines for considering the place of humans in their interaction with the system throughout its life cycle. Parts of the techniques of the HSI paradigm aim at involving end-users in the design process to understand their needs and to ensure that the system meets them. This involvement can be done through interviews or human-in-the-loop simulations for example.

Industrial usability is a major concern of the research laboratories ESTIA Recherche⁴ of ESTIA Institute of Technology⁵ and the LGI⁶ of CentraleSupélec⁷. The research teams focus on the study and improvement of HSI techniques in industrial contexts. TotalEnergies⁸ R&D wished to improve the capitalization and management of knowledge, to be integrated into tools available in a control room in standard and remote operational conditions and entrusted ESTIA Recherche to perform a study in this domain.

Safety being their first value on their industrial sites, TotalEnergies studied the impact of the implementation of new detection sensors on its installation to provide faster real time and contextualized information to the operator supervising it from a control room. This new way to receive information is intended to help control room operators dealing with site supervision in eventual downgraded situations. Downgraded situation is defined by the Exploration and Production branch of the company as *"any abnormal situation where the installation is operating outside its design concept, resulting in an increase in operation-related risk"*. In this context, the company provided the study with an industrial use case to focus on the impact of these information on the human in the control room. The company also allowed to access expert operators from the domain to both provide knowledge on how the work is really done and participate to human-in-the-loop tests. After studying the cognitive phenomena that influence humans in their decision making, the choice was made to focus on improving the ability of humans to grab on reality and the means to ensure it by using a digital twin (DT). The digital twin is here a decision support tool, notably by improving the comprehensibility of the system.

System intelligibility is a question of how the human operator can understand the operation of the complex system and to make informed decisions about it. This human phenomenon has been translated in the literature as the principle of Situation Awareness (SA) (Endsley 1995). It has therefore become important to find means to

⁴ <https://www.estia.fr/recherche> (accessed last 25/07/2022)

⁵ <https://www.estia.fr/> (accessed last 25/07/2022)

⁶ <https://www.centralesupelec.fr/fr/laboratoire-genie-industriel-lgi-ea-2606> (accessed last 25/07/2022)

⁷ <https://www.centralesupelec.fr/fr> (accessed last 25/07/2022)

⁸ <https://totalenergies.com/fr/developpement-durable/bien-etre-des-personnes/sante-securite> (accessed last 25/07/2022)

support it through systems that provide the user with a vision of the situation. It was therefore important to provide a detailed methodology for the design and implementation of these means.

Consequently, this work aims at defining a design methodology to create a Situation Awareness Support System (SASS) to help decision making in abnormal situations. This was achieved through applied research following the HSI paradigm. This applied research was structured in three parts that are defined as follow.

In the first part, the focus is on the phenomenon of human decision making and the means to support it. Starting from the scientific positioning of complex systems as an aggregation of components making a system difficult to understand, we introduce the need to support human decision making in front of such systems and propose different models to understand how to support human decision making. Through these models, the importance of the concept of situational awareness is highlighted. After detailing ways to support humans in their interaction with complex systems, we focus on tools to support human decision making. As in previous sections, once the general decision-making capabilities of these systems are defined, the focus shifts to the phenomenon of situational awareness. In the context of these situational awareness support systems (SASS), the case of the digital twin is discussed in more detail. After defining the concepts of the digital twin from the literature, its technical structure is questioned in light of its ability to support situational awareness.

In the second part we focus on a methodology to ensure the design of a SASS. A SA-centered design methodology review of the literature showed the lack of a detailed methodology that uses the techniques from the HSI field. To address this shortcoming, we have defined the Reality Anchor Methodology (RAM). The structure of this methodology is then presented and justified. Based on the definition of the user's needs through a study of company rules and interviews, the situational elements that the user needs to gain situation awareness and make an informed decision, called Reality Anchors (RA), are defined. Then, to ensure the validity of the defined Reality Anchors, a prototype is implemented and tested with domain end users. Thanks to these tests, several evaluations can be performed to assess the SASS.

Finally, the third part focuses on the application of the Reality Anchors Methodology (RAM) to a use case in the oil-and-gas sector of the company TotalEnergies transferable to new energies activities. The chosen use case was defined as the management of gas leak by control room operators on an offshore platform. During this study, the rules and regulations from TotalEnergies were studied to elicit the management process in cases of such abnormal situation. This general process was compared to the one defined after running interviews with domain experts to generate a set of reality anchors used by control room operators to make decisions in the event of a gas leak.

Introduction

This set of reality anchors was then implemented in a prototype simulating a digital twin of an offshore oil-and-gas platform. This digital twin simulation was used to collect results on its performance regarding its impact on situation awareness. These results were finally used to draw conclusions about the impact of the prototype on the user's situation awareness and define ways to improve the prototype and its ability to provide situation awareness.

Part I: Control rooms operator support

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Introduction

TotalEnergies' industrial challenges to improve company regarding safety have led to the need to better understand complex systems involving humans. Understanding this type of system enables to manage them and make decision upon it. However, to better support humans in their decision-making process, the literature from the domain must be explored as well.

This section proposes to set the basement of the study and to enable to understand the concepts of complex systems, decision making, situation awareness and the ways to support this last cognitive phenomenon. Moreover, this section pushes to define the concept of digital twin as a tool to support situation awareness.

I.1 Complex systems

Systems have become increasingly complex over the years. Cars are an excellent example of this increase in complexity. Years back, cars, like a Citroen 2CV for example, where composed of a limited amount of simple mechanical components; even with limited knowledge one could identify each component, its function and perform maintenance action for example. However, today's cars use computers and sensors added to the mechanical and electrical components of the system. The number of components has increased, every component is now a system in its own, and their identification has become difficult for non-experts. Finally, the behavior of this system has become even more difficult to diagnose and understand because of the interactions between its subsystems.

In this section, we will look at the definition of complex systems from several angles and open the question of the relationship between these systems and humans, as the amount of these complex systems increases in our society.

I.1.1 Definitions

The notion of **system** is defined in the Oxford dictionary in the light of multiple concepts and domains:

- From a conceptual point of view, a system is "an organized set of ideas or theories or a particular way of doing something".
- From a technical point of view, a system is defined as "a group of things, pieces of equipment, etc. that are connected or work together".
- From a computer science point of view, a system is defined as "a set of computer equipment and programs that are used together".
- From the biological point of view, a system is defined as "a human or an animal body, or a part of it, when it is being thought of as the organs and processes that make it function".

- From a political point of view, a system is defined as “the rules or people that control a country or an organization, especially when they seem to be unfair because you cannot change them”.

In examining the concepts used to define the notion of system, it appears that all these definitions have in common the concept of a system as a group of elements. Furthermore, these definitions bring together elements that function in a similar way, together and toward the same goal.

Systems engineering is a research field focused on the study, design, and management of systems. The International Council on Systems Engineering (INCOSE)⁹ has proposed a theoretical and operational definition of Systems Engineering (SE) (Sillitto et al. 2019). They defined a system as “an arrangement of parts or elements that together exhibit behavior or meaning that individual constituents do not” (see Figure I-1).

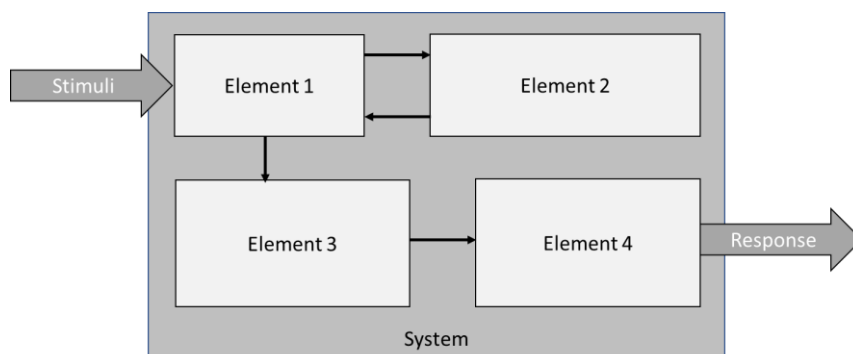


Figure I-1: System model.

Using the car as an example, we can identify two different elements: (1) the steering element and (2) the propulsion element. While the steering element allows the car to choose a direction, it does not allow the car to move forward and thus to reach to a specific location. By the same token, the propulsion element allows the car to move without human assistance. However, a car with only a propulsion element will only be able to move to a specific location. It is by combining the two elements that the car will allow a driver to drive to a specific place.

In addition, a system may be composed of other systems that may be physical systems, defined as “an arrangement of parts or elements that together *exhibit a behavior* that the individual constituents do not”, and/or conceptual systems defined as “an arrangement of parts or elements that together *exhibit a meaning* that the individual constituents do not exhibit”. That is the concept of system of systems. This concept is illustrated in Example I-1.

⁹ <https://www.incose.org/> (accessed last 25/07/2022)

Example I-1: Off-shore platform system component decomposition example

Following this decomposition, it is possible to break down an offshore oil-and-gas platform into subsystems (see Figure I-2). For example, an oil-and-gas platform is a system composed of process subsystems (with physical systems) like compressors and parts such as flow lines that allow the industrial process to be performed. In addition, it is also composed of social subsystems (with conceptual systems) that are the human organization on site, in the control room or maintenance for example.

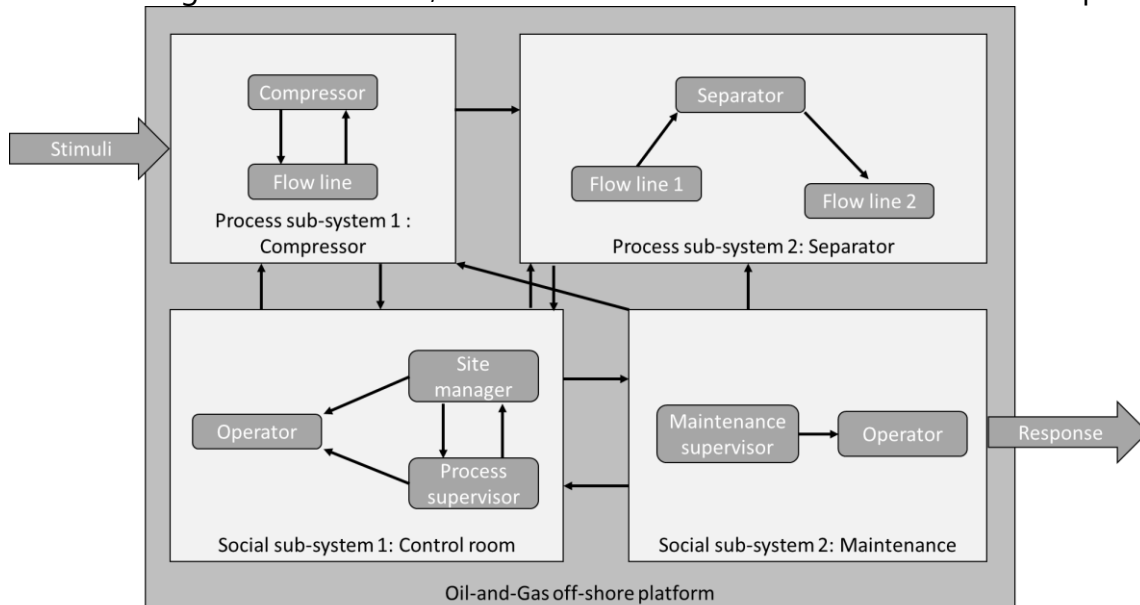


Figure I-2: Off-shore platform system model

Following the systemic approach, the decomposition of systems into subsystems allows to represent and iteratively decompose large systems into more manageable systems. This decomposition allows the analysis, design, and evaluation of complex systems.

Complexity is defined in the Oxford dictionary¹⁰ as “the state of being formed of many parts; the state of being difficult to understand”. Technological progress has allowed people to create a wide variety of systems that can interact with each another. Each system serves specific purposes, and systems of systems have emerged to serve many purposes. Systems of systems are more difficult to understand because they involve many different technical areas that must interact with each another.

In the field of systems engineering, a **complex system** is defined as “a group or organization which is made up of many interacting parts” where “the interactions between them often lead to large-scale behaviors which are not easily predicted from

¹⁰ <https://www.oxfordlearnersdictionaries.com/definition/english/complexity?q=complexity> (accessed last 25/07/2022)

a knowledge only of the behavior of the individual agents” (Mitchell and Newman 2001). This behavior of the complex systems is represented in Example I-2.

Example I-2: Example of the complex action/effect paradigm on an oil-and-gas site.

This definition can be illustrated using the example of an offshore oil-and-gas platform.

Closing partially a valve on the process line (which is part of the physical process subsystem) directly affects the flow rate in the following pipe and affects the pressure input along the line. This phenomenon is predictable.

Along the line, this effect on the pressure input will force compressors to consume more energy to keep up with their setpoint (i.e., the value that must be followed for the process to work properly). This can only be predictable by knowledge of the process.

However, if this previous effect might be predicted by process experts' operators, increasing the compressor workload might increase the noise and impact the communication ability of close onsite operators. This behavior can be defined as unpredictable.

These large-scale effects, which are difficult to predict, are like the butterfly effect (Lorenz 2001), where one stroke of the butterfly can create a tornado halfway around the world. The definition of the butterfly effect is an example of the need for theories to help understand these systems.

I.1.2 Complexity theories

Theories and models have emerged to understand and predict the behaviors of complex systems (Boccaro 2010).

Manson (Manson 2001) has proposed three types of complexity theories, (1) algorithmic complexity, (2) deterministic complexity and (3) aggregate complexity, in order to support a holistic vision of complex systems.

I.1.2.1 Algorithmic complexity

Algorithmic complexity formalizes system complexity using mathematical science and information science.

Mathematical science enables modeling and measuring algorithmic complexity using a mathematical model of the behavior of a complex system. For example, sorting algorithms enable the assessment of the complexity of a system, and to choose the best algorithms for its use and therefore reduce system algorithmic complexity.

In information theory, the interactions of subsystems are reduced to measures that can mimic systems behavior (Chaitin 1990). For example, correctly identifying the data

needed for a system to work as needed can reduce the amount of data and thus the complexity of the system.

Overall, algorithmic complexity focuses on solutions for scaling mathematical algorithms to work with complex systems; algorithmic complexity is an indicator of how the problem can be addressed by computational methods. It is also difficult to apply it to social and environmental phenomena as it is difficult to represent social behavior through mathematical algorithms. Also, algorithms apply a finite set of instruction to a finite set of input data. An agent travelling the world gets data along the execution of its instructions. Algorithmic complexity can be extrapolated to this case but does not a really fit. However, this vision of complexity could be used in the oil-and-gas domain as discussed in Example I-3.

Example I-3: Example of algorithmic complexity.

Continuing with the example of an offshore platform, the different complexity theories presented earlier give different view of the complexity of the system. The maximum flow problem can be used to represent process optimization challenges regarding the maximization of a flow rate on an oil-and-gas production site. Given the algorithmic complexity, it is possible to define the complexity of such algorithm and by extension define the complexity of the flow network system.

I.1.2.2 Deterministic complexity

Deterministic complexity focuses on the impact of major components on the behavior of the system. Deterministic complexity is related to chaos and catastrophe theories. Chaos theory defines two types of chaos: **True chaos** is considered random where **robust chaos**, while appearing random, follows an underlying order. Catastrophe theory defines a logic between small changes leading to large changes in the behavior of the complex system.

Following these theories, deterministic complexity is defined as the following four key components: (1) the use of deterministic mathematics and mathematical attractors, (2) the notion of feedback, (3) the sensitivity to initial conditions and bifurcation; and (4) the idea of deterministic chaos and strange attractors.

With the description of the behavior of complex systems by mathematical function appears the notion of mathematical **attractor** (May 1976). An attractor is a value toward the function or system tends to evolve in time. Such a concept allows to predict partially the behavior of complex systems.

In the mathematical model representing the system, the future states of the system variables (temperature, ...) are expressed as functions of current state; for example,

tomorrow's temperature depends on today's temperature. Among these dependences, some are defined as **negative feedbacks** that lead the variables to tend towards a stable state (as in the exothermic reactions, Le Chatelier's principle (Lin and Murphy 2017)) while other are **positive feedbacks** that lead the variables towards points of no returns (whether zero or infinity) (Manson 2001).

Sensitivity to initial condition represent the ability of a complex system to radically change its results depending on its initial conditions. A representation of this concept can be seen in the "butterfly effect" where a change in the initial condition can lead to large scale effects. This concept must be associated with the ability of the behavior of a system to move from following one attractor to another, called bifurcation (Feigenbaum 1980).

Sometimes the behavior of the system can become chaotic with no discernible normal attractors. However, such conditions may not provide a normal attractor, but at least possess a **strange attractor** towards which the values will tend without ever reaching it.

Overall, deterministic complexity defines complex systems using two or three principal elements. However, defining a complex system using up to three principal elements may reduce the complex system too much (Kellert 1993). This view of complexity could be used to evaluate the complexity of parts of an oil-and-gas platform such as the one illustrated in Example I-4.

Example I-4: Example of deterministic complexity

Continuing with the example of offshore platform, the different complexity theories presented earlier give different vision of the complexity of the system. Considering deterministic complexity, the change of state of the platform, from its design state to an abnormal state for example, would be defined based on specific key elements. For example, the complexity of the gas leak evolution phenomenon could be defined based on its flow rate with as an attractor with negative feedback bringing this variable to a stability once the pressure and hole size are stabilized.

I.1.2.3 Aggregate complexity

Aggregate complexity focuses on how individual elements interact together in the complex system. To focus on these interactions, aggregate complexity relies on defining the relationship between entities, internal structure as well as the surrounding environment, learning capabilities and emergent behavior, and how the complex system evolves (Manson 2001).

Complex systems are defined as being composed of multiples components. These components have relationships with each other as they exchange information,

knowledge, and impact each other. These relationships are difficult to define holistically and are expressing complex behavior.

Furthermore, in complex systems, the components and their relationships form a structure called the internal structure. This internal structure is composed of sub systems classified by different factors such as physical proximity or role on the platform. This structure is impacted by the environment in which the system is embedded. This impact on and from the environment is therefore important in this vision.

As the complex system lives through its environment, the internal structure and subcomponents form a memory. The relationships between components are complex themselves and evolve.

Interaction among the components can lead to the emergence of a function. Complex systems are composed of multiple interactions and components making the emergence of phenomenon that are beyond prediction capabilities. Such a system is constantly self-organizing, learning from previous cases or even in specific critical situations.

In conclusion, aggregate complexity is the most holistic view of complex systems. However, such holistic view makes it difficult to implement as the boundaries of the system can be difficult to define. In the case of an oil-and-gas platform, this vision of complexity would take the form of Example I-5.

Example I-5: Example of aggregate complexity

Continuing the example of offshore platform, the different complexity theories presented earlier give different view of the complexity of the system.

If we were to follow the paradigm of aggregate complexity on an offshore platform, the components of the system can be defined as the operators on site, the operators in the control room, the equipment of the process performed on the platform and many others. Each of these components have different interactions between one another in the system. For example, a control room operator and a production authority can both be part of an operation control subsystem and interact to manage the production. This control room is therefore a part of the internal structure of the system.

Regarding the environment, an offshore platform is in the middle of the ocean and its components are therefore impacted by salt water, the wind, the swell and other environment element.

An offshore platform will be in constant evolution as components of the process will be adapted, new detectors can be added or rules can be upgraded, based on past event as the system learns. This forms the memory of the system.

Regarding this evolution of the system, on an offshore platform, the evolution of a parameter, such as the wind speed and direction, can impact the system and prevent gas leak detection for example. The lack of detection can then have a subsequent

impact on the system that will be difficult to predict because the system is constantly changing and promote the emergence of functions.

I.1.2.4 Synthesis

It appears that, according to the three complexity theories mentioned above, different points of view have been used to quantify, represent, and understand complex systems.

Algorithmic complexity uses algorithms translating system behavior to mathematically evaluate the complexity of these algorithms. However, if the definition of algorithms for mechanical processes, computing or physical phenomenon is performed for years, translating humans' behavior through algorithms appears as more difficult. As this study focuses on humans' roles in the system, this complexity theory would not be able to translate fully to the studied system.

Deterministic complexity uses main elements of the system to represent its complete behavior and define its complexity. By following the defined logic of the evolution of the elements, it can develop an understanding of the behavior of the complex system. However, this theory assumes that the chosen principal elements represent the complete system and therefore reduces the scale of the system. This theory, which aims to work on a full-scale complex system and understanding every component impact to help in decision making, is not reflected in the study performed.

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.

For the reasons listed above, this study will follow the aggregate complexity approach to represent the system using components. This approach will allow to take into consideration the humans involved in the system behavior to support them, in their interactions with the other components of the system. More than considering the components of the system, this approach aims to consider the interaction and the impact of the environment on the system.

I.1.3 Human and complex systems

According to the aggregate complexity paradigm (Manson 2001), and as already mentioned previously in the text, humans can be considered as components of the complex system. According to this same paradigm, those components have relationships with each another, with other components, and with the environment of the system. Since humans are known to be complex by nature, it is not surprising that systems composed of humans are complex. A better understanding of such a system can therefore be partially achieved by focusing on humans in complex systems.

Interactions between human components of the system can be from a human interacting with a physical element, other humans, both, or the environment (see Example I-6).

Example I-6: Example of the four types of interactions between humans and other systems.

Considering the offshore oil-and-gas platform system, it is possible to study the multiple humans that are part of it. By taking four example of humans that are part of the system, it is possible to identify four types of interactions:

- Nearby boats pilots are part of the environment and **can be affected and can impact** the offshore platform in the event of a collision, for example.
- The role of the maintenance operators will be to **physically act** on the system and to be in direct contact with any possible equipment in the system.
- The production supervisor will have an impact on the humans who are part of the system (ex: field operators) because he or she is the **authority** figure of the system.
- Control room operators have the role of managing both humans and other components, as they **coordinate** the maintenance operators and **regulate** the process through actuators.

As shown in this example, humans have a role of management of the system and this study aims at supporting this human capacity. Managing complex system requires an understanding of the system being managed. In the case of a complex system composed of multiples elements, the representation of these elements to the decision maker is important to allow him/her to access information about the system. However, as explained in the previous sections, understanding a complex system is not trivial and may need several approaches to create a complete view of the system.

Therefore, the relationship between humans, as part of the system, and the rest of the complex system must be the subject of system studies to better manage them. While the system engineering discipline has been addressing the understanding and modeling of systems, and focusing on complex systems for years, the place of humans in complex systems is a younger concern. INCOSE Human Systems Integration (HSI) Working Group¹¹ has taken up this issue. This working group focuses on defining guidelines and practices for designers to identify ways that systems can be designed to integrate humans in complex systems. This working group brings together theories from engineering and the humanities.

¹¹ <https://www.incose.org/incose-member-resources/working-groups/analytic/human-systems-integration> (accessed last 25/07/2022)

Following this paradigm, this study focuses on adopting a perspective centered on humanities to understand human practices with management tools in complex systems. The first step in understanding the management capabilities of humans in a complex system is to examine decision-making processes. These processes are detailed in the next section.

I.2 Humans Decision-Making in complex systems

Decision-making is part of everyday life, whether consciously or unconsciously. As we have seen previously, in the case of complex systems management, decision making is not trivial. This section begins by defining the concept of human decision making to provide a better understanding of the various underlying cognitive phenomena. By examining the situational awareness, which is one of these cognitive phenomena, this section provides guidelines for improving decision-making and assisting people in their various decision-making processes.

The concept of decision making is commonly defined as “the process of making choices” (Cambridge dictionary¹²). Theories emerged from multiple fields focusing on the selection of “the best option from a choice set containing two or more options” (Beach 1993). Since the way the choice depends on the situation, different models have been developed to characterize this human capacity. Several types of decision-making processes have been defined in literature.

According to Simon (Simon 1960), the process of making decisions where the process is clearly identified, is called structured decisions-making. In contrast, unstructured decision-making process doesn't have a clearly identified process and can be defined as a “set of actions and dynamic factors that begins with the identification of a stimulus for action and ends with the specific commitment to action” (Mintzberg, Raisinghani, and Theoret 1976). This study focuses on the later as operators may face unexpected situations.

As shown in the last section, understanding a complex system generally requires a holistic point of view. Decision making models have been defined with the aim at representing and understanding the way human make decisions. Understanding these models and the factors intervening in the process will allow us to define a human decision-making approach for complex systems.

I.2.1 Decision making model

A model is defined in the oxford dictionary, when related to systems, as “a simple description of a system, used for explaining how something works or calculating what might happen, etc.”. To understand how human decision-making works, models of the phenomenon have been defined from different perspectives. Examination of these

¹² <https://dictionary.cambridge.org/fr/dictionnaire/anglais/decision-making> (accessed last 25/07/2022)

models provides a better understanding of the decision-making process. As decision-making is a human ability, it appears as important to first look at the decision-making models from the psychology domain.

I.2.1.1 Ethical decision making

Considering the foundation of the field of decision-making in psychology, Rest's four-step model (Craft 2013; O'Fallon and Butterfield 2005; Rest 1986) appears as a basis for models that have emerged to characterize decision-making. The four-step model consists of:

- The recognition of the moral issue where the awareness of the moral situation must be made,
- The formulation of a moral judgment where courses of action are judged to be moral or not,
- The establishment of moral intents where the moral courses of action will be prioritized,
- The engagement in a moral behavior where the moral intent is applied to the situation.

This basic model was then updated with the addition of the concept of moral intensity to become a six components model (Jones 1991) (see Figure I-3). This model includes the Rest's four components model in addition to the moral intensity and organizational factors components.

The model is composed of a set of factors representing the moral issue.

- The magnitude of consequence is defined as "the sum of the harms (or benefits) done to victims (or beneficiaries) of the moral act in question."
- The social consensus is defined as "the degree of social agreement that a proposed act is evil (or good)."
- The probability of effect is defined as "a joint function of the probability that the act in question will actually take place and the act in question will actually cause the harm (benefit) predicted."
- The temporal immediacy is defined as "the length of time between the present and the onset of consequences of the moral act in question".
- The proximity is defined as "the feeling of nearness (social cultural, psychological, or physical) that the moral agent has for victims (beneficiaries) of the evil (beneficial) act in question."
- The concentration of effect is defined "an inverse function of the number of people affected by an act if given magnitude."

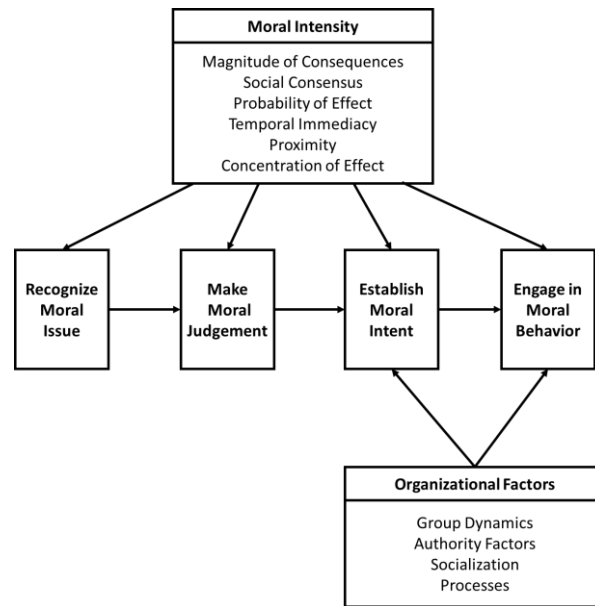


Figure I-3: An Issue-Contingent Model of Ethical Decision Making in Organizations (Jones 1991)

The organizational factors component is composed of factors involving moral agents. These factors are (1) group dynamics, (2) authority, (3) socialization, and (4) processes. They interact with each other to affect moral reasoning and thus the outcomes of establishing moral intention and engaging in moral behavior.

Example I-7: Example of ethical decision making in the oil-and-gas domain.

Taking the example of a decision on an oil-and-gas off-shore platform, ethical decision-making appears in the case of decision linked to the exposition of intervention team to hazards when needed.

Following the previously defined model, the first step is in the recognition of the moral issue. Exposing humans to known hazards to save others can be defined as a moral issue.

Regarding the defined moral issue, judgement can be made that not intervening gets to the absolute certainty of **impact** from the hazard to the less prepared operators on site. Moreover, intervention of prepared and properly equipped intervention team members could save their lives with less risk of impact as they are trained.

Then the moral intend is defined. In this case, it is right to try to save people rather than condemned them.

Finally, this intend leads to engaging the decision to send the intervention team members to save on-site personnel.

In this example, moral intensity factors can be found where a social consensus is that letting people with high certainty of harm is wrong, the probability of impact on the different involved humans would it be firefighter or operators or even the proximity as the involved operators are part of the global social system of the offshore platform for example.

Ethical decision making, considering the field of psychology, highlights the factor involved in human decision making in relation to other humans. This process begins with defining the situation in which the decision maker finds himself or herself before evaluating the situation considering a specific goal, that goal being in this case to be morally right. Then the decision is made, and action is taken.

This provides a general direction to look for in understanding decision making in the oil and gas field, as humans are involved in the situation. It also gives direction to the factors that qualify the situation in the form of impact of the decision, probability of effects, or temporal immediacy. However, this process is global and does not consider the impact of external factors, such as the effects on an oil and gas process for example. As we said at the beginning of this section, working with complex systems requires looking for other models that take other factors into account to refine the picture of how humans manage complex systems.

I.2.1.2 Organizational decision making

Working with complex systems and abnormal situations in the oil and gas field, **organizational decision making** should further define the decision-making process of the field more precisely.

Based on a study of 25 decision-making processes, a general model of the decision-making process was developed by Mintzberg (see Figure I-4). This model is developed to be adapted to different cases, but three main parts are common to every decision that is (1) the identification of a given decision to be made, (2) the development of a solution and (3) the selection of the associated decisions.

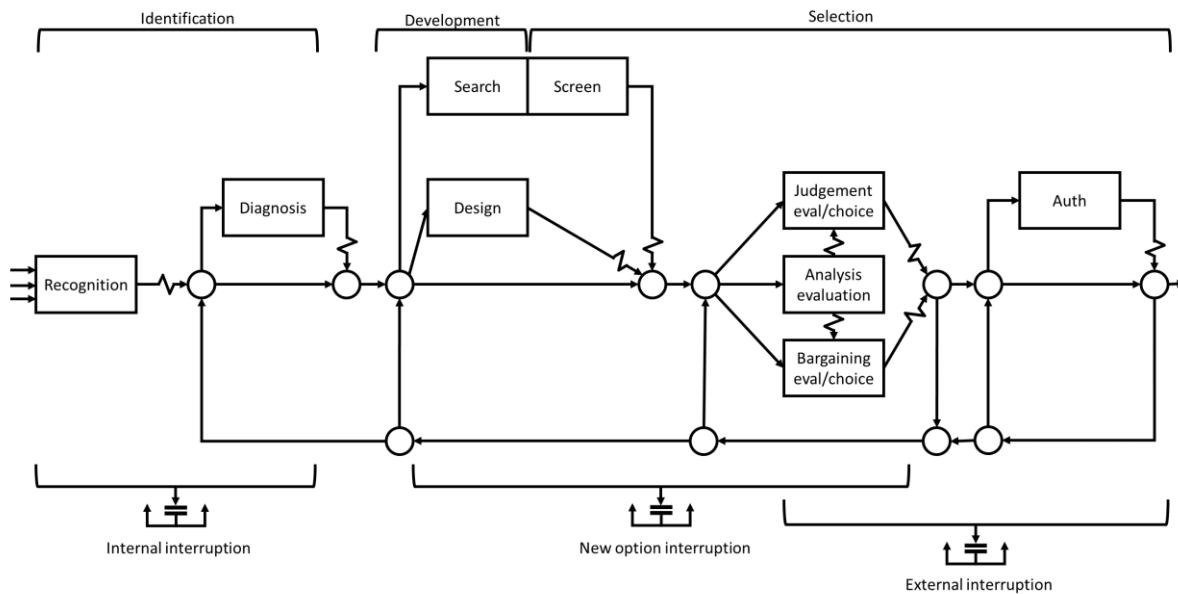


Figure I-4: General model of the strategic decision process (Mintzberg et al. 1976).

During the identification phase, the decision maker recognizes the need for a decision from a difference in the current situation and an expected situation. This phase can be started from different stimulus. In the case of oil-and-gas management, the triggering of an alarm is a situation that is not to be considered as expected. However, stimulus can be less recognizable and may appear from the recognition of deviation in a process value for example. Once the decision-making situation is recognized as so, the decision-making process starts. First, the decision maker should diagnose the situation and try to regroup more information from the situation increasing its understanding of the situation. According to Mintzberg's study, the diagnosis step is influenced by time constraints and this step is therefore more present in problem solving (long term decision making) than in decision of opportunity and crisis solving.

During the development phase, the decision maker produces one or more solutions to bring the situation back to the expected situation. This phase can be subdivided in two different routines that are (1) the search for an *already made solution* or (2) the designing of a *new solution*.

The search routine can be seen as following different types of search patterns to find *predefined solutions*.

Solution design is a complex process that can take the form of a *fully customized solution* or the adaptation of a *predefined solution*. This solution design process is defined as iterative and starts with an image of an *ideal solution* that evolves through the design steps to crystallize into a feasible solution.

In the selection phase, the decision maker chooses the solution to be applied as a final step in the decision-making process. This phase consists of three main routines: (1) the

screen routine, (2) the evaluation-choice routine and (3) the authorization routine. First, the screen routine follows the search routine and focuses on eliminating infeasible solutions based on the constraints of the situation. For example, if the solution implementation time is too long the solution can be considered as infeasible. Then, the evaluation-choice routine sees the implementation of a solution scoring to identify the best solution with respect to the decision maker's objective. Finally, the authorization routine is used when the decision-maker does not have the authority to commit to the actions necessary to implement the chosen solution.

The three stages of the decision process outlined are a simplified model and the reality is rarely that simple. Therefore, variations in the process can be identified:

- After the identification step, ready-made solutions are looked after but if not found, a new solution is designed.
- The solutions are then analyzed and evaluated before a choice is made. If no solutions are evaluated as correct than the process loop around to the needed step until a satisfactory solution is elected and authorized if necessary.
- Interruptions can occur at different time in the process and bring evolution to the process.
- At the same time, delays may occur in the process as represented in the form of the broken arrows.

If we consider the organizational decision-making model, it gives a more detailed idea of the decision-making process as it can be achieved while managing a complex system. From a psychological point of view, the process begins with a need for the decision maker to become aware of the situation he/she is facing. Solutions are then defined and evaluated to select the one that best suits the situation. This solution will then be applied to act on the situation and bring it to an expected state.

Example 1-8: Example of application of the organizational decision-making model steps.

Applying the organizational decision process model to an oil-and gas off-shore platform the different phase of the process can be illustrated as follow in the case of an anomaly appearing on the platform:

The recognition of the situation can be performed by a control room operator spotting the pressure decreasing that may signify that a leak is occurring in the flowline.

In this case, the diagnosis step is performed by the operator that have found the situation and uses its knowledge to diagnose the problem or by the Health Safety Environment (HSE) supervisor that would gather a team of "experts" to diagnose a reported abnormal situation.

Then the search for a solution can be performed using defined company procedures or employees' memory and experience (Return of Experience or REX).

If the search for solution does not provide an easy to implement and fast solution for the case, a designed solution would be to isolate and depressurize the line and to send operators on site to repair the leak.

The defined solution will be screened to determine if the time to implement it will be too long or if the equipment is accessible for example. If those criteria can't be validated the solutions can be considered as infeasible.

Once the solution is considered as feasible, it is evaluated to define the best solution. In the oil-and-gas domain the major goal will be to protect the humans on site and therefore, solutions will be classified flowing their ability to protect humans

Finally, in the case of a solution calling for a team to perform an intervention on an oil-and-gas site, the site manager will have to authorize the intervention.

1.2.1.3 Synthesis

The two views of decision making presented in this section introduced general models explaining the process of human decision making.

From a psychological point of view, the decision aims at providing the right answer to a problem from an ethical point of view. This four-component model highlights the identification of the situation, definition of the solution, the evaluation of the solution and the application of the solution.

From the organizational point of view, any decision-making model aims at defining the best solution for the identified problem. This model is based on three main steps, identification, solution development and selection of the best solution.

Both introduced models show the importance of the context would it be moral or technical. This "identification" step being the first stage of the models, it gives the base for the decision-making process. This stage is related to the decision maker's ability to have situational awareness.

In the case of complex systems, having good situational awareness is more necessary as we have seen that these systems are sensitive to initial conditions. Helping the decision maker to have good situational awareness would support his/her ability to make good decisions on complex systems. Therefore, this study focuses on the situation during the decision process and its identification by the human decision maker.

1.2.2 Situation awareness

As we have seen previously, in the case of complex systems, the decision-maker cannot easily understand the system by simply "looking at it". Indeed, complex systems are composed of many subsystems and their combined behaviors are difficult to define and predict. However, as we saw in the last section, deciding upon a system requires the decision maker to be aware of the situation related to the system. This ability is

called **situation awareness** or **situational awareness**. In this case, the process of acquiring situational awareness is therefore a major concern (Endsley 1995).

As with decision making, different views of the concept of situational awareness have emerged over the years (Stanton et al. 2010). Three of these are detailed in the following sections: in the disciplines of (1) psychology, (2) computer science/engineering, and (3) human factors.

I.2.2.1 Psychology point of view

From the perspective of the field of psychology, **situational awareness** is most broadly 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). This process is defined as an individual psychological phenomenon that occurs in the minds of decision makers. This definition is accompanied by a three-level model (see Figure I-5):

- The **perception**, where the decision-maker will perceive elements of the situation independently. Those elements are provided by human senses and therefore can be sounds, visual signals, tactile signals or olfactive signals.
- The **comprehension or understanding**, where the elements will be set in relation to one-another based on knowledge to define a model of the situation. For example, an alarm sound will be comprehended as a problem detection and put in relation with a light signal or letters linked together to form a word and associate it's meaning in the decision maker language.
- The **projection**, where the possible evolutions of the situation are defined based on the defined model and knowledge. For example, if a fire alarm is comprehended and situated on a specific point of the system, the user can project the situation and imagine that a fire would start from this area or project that the automatic fire extinguishing system will put it out by itself.

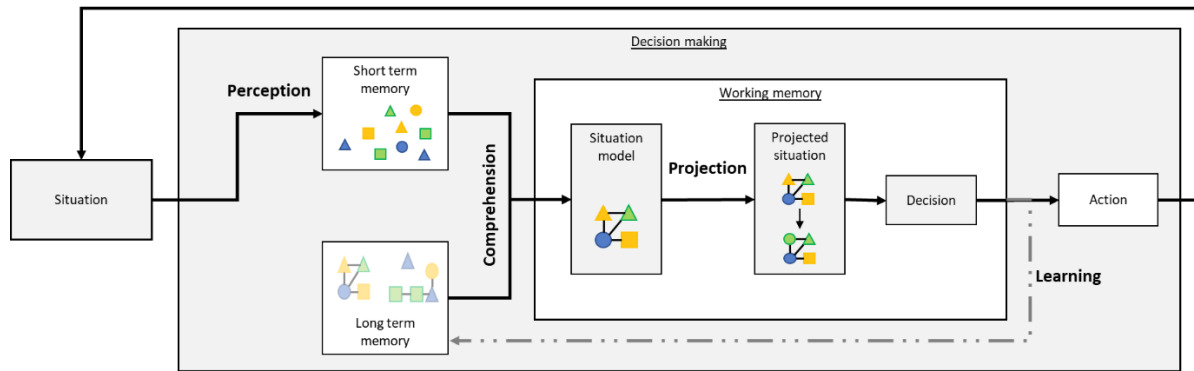


Figure I-5: Situation awareness process in decision making inspired by Endsley (Endsley 1988)

This phenomenon is based on the notion of **user attentiveness**, which represents the ability of the user to focus on the situation, as well as on three types of memories:

- The **short-term memory** serves as storage for perceived elements of the situation. These elements are acquired from the situation through the perception process.
- The **long-term memory** serves as storage for previous known situation models and the link known link between situation elements enabling both comprehension and projection.
- Finally, the **working memory** is actively used during the complete process and is where the information and knowledge from the short-term and long-term memories are linked together to create models of the current situation. This memory is used to store the current situation model and the projected situation model.

This model aims to define the process of decision making for a single decision maker and put this model in relation to human information processing concepts. This representation of situational awareness is limited to an individual and does not include behavior outside of its cognitive process. It has been criticized for not being able to represent a satisfactory team model of situational awareness (Salmon et al. 2009).

1.2.2.2 Computing/engineering point of view

From an engineering perspective situation awareness is the fact that *data* and *information* from the world are provided to the decision maker through a technological medium.

Let's precise the notions of data, information, and knowledge. In this study, we define them as follow based on (Tuomi 1999) et (Rakoto, Hermosillo, and Ruet 2002) (see Figure I-6).

- **Data** is defined as simple facts and values. For example, 54 is a data.
- **Information** is defined as contextualized data. For example, 54 kg/s is a flow rate.

- **Knowledge** is defined as generalized information. This knowledge can be formalized through expertise or experience. Knowledge coming from expertise is a theoretical form of knowledge acquisition. Experienced knowledge is acquired through living situations. For example, "54kg/s is a low flow rate" is knowledge based on expertise knowledge.

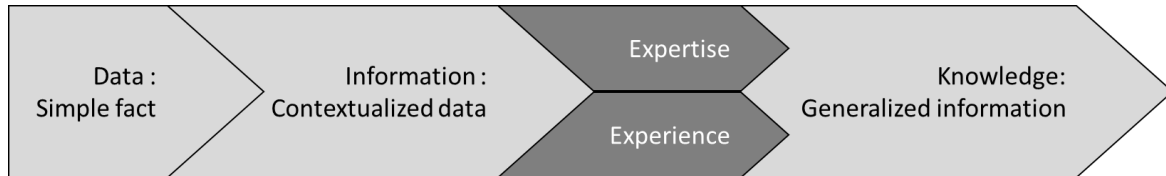


Figure I-6: Representation of data, information, knowledge relations.

Following this technology-centric view, it is defined that "situational awareness is achieved by integrating a myriad of technologies to provide users with access to information based on their circumstances" (ESRI 2008).

This view of situation awareness is directed toward system designers and engineers that aim at providing element of the situation through technology. This is achieved by displaying information related to the situation. It is therefore considered that the ability from technological systems to tell people information about the situation they are in and providing them their situation awareness (Carroll 1999). Studies with military pilots have shown that pilots consider their displays to contain their situational awareness (Jenkins et al. 2008). Situational awareness is therefore not a personal psychological concept in the mind, but a collection of data and information provided by a technological tool.

Example I-9: Example of situation awareness from the engineering point of view.

Taking the example of current control room operating tools in oil-and-gas sites, operators situation awareness is composed of the data and information provided by the tools. The situation is therefore composed of:

- The process organization, which equipment are in the process and in which order of operation.
- Process values at specific point provided by sensors, like pressure, flow rate, and temperature in pipes.
- Trends showing the evolution of the process parameters.
- The status of equipment, which equipment is running, or which valve is open.

These elements provided from the tool are example that would define the operator situation awareness in an engineering point of view.

This representation of situation awareness, as data related to the real world that is displayed by technology medium, supposes that the more information are available in the display the better the situation awareness will be. However, it is point out in the

literature that factors like information overload, poor interpretation, non-relevant information, or false data would rather degrade situation awareness. Moreover, the way data and information are presented to the decision maker will affect the decision making (Endsley and Jones 1997). Therefore, if this vision of situation awareness finds a concrete application for system definition it lacks a link with other human known phenomenon that make improving human situation awareness more difficult.

I.2.2.3 Human factor point of view

From a human factors perspective, situational awareness is neither an individual phenomenon nor a collection of data and information from a technological system, but the result of the coordination form the two. This idea found ground with the idea of **distributed situation awareness** that could describe people working with one another as well as how information is the link between people and technology (Stanton et al. 2006). The distributed situation awareness theory considers both humans and technological systems as being agents, human or non-human actors of the complex system, and having a distributed situation awareness. It combines a systemic point of view with the three levels of situation awareness defined by Endsley (Endsley 1995).

Example I-10: Example of distributed situation awareness.

Taking the example of gas leak management in oil-and-gas control room the situation could be developed as shown in Table I-1 with the interaction between 3 agents of this complex system being a gas sensor on site, the control room operator, and the site manager. In this situation:

- The gas sensor can detect the presence of flammable gas. It will provide the concentration of gas in the air as part
- The control room operator will be alerted and will read the concentration of gas on the sensor. Based on the displayed level it will comprehend the presence of a hazard to human based on his expertise/experience. It will therefore project the effects on human and the need for an evacuation of the area around the sensor.
- The site manager will perceive the operator evacuating the concern area. It will comprehend that there is a risk in the area and that this risk may affect the whole site. It will therefore project the possibility of a full site evacuation.

Table I-1 Example of distributed situation awareness based on Stanton and al.(Stanton et al. 2006)

AGENT	GAS SENSOR	CONTROL ROOM OPERATOR	SITE MANAGER
Perception	Detects concentration of gas	Hear the alarm and read the concentration of gas on the interface	Is informed of local evacuation order
Comprehension	Calculates gas concentration in the air and compare to alarm threshold	Determines gas concentration can be hazardous for operators working in the area	Understand that a problem is occurring and could impact the entire site
Projection	Indicates that gas concentration could reach lower flammability limit	Needs to evacuate operators in the leak area	Prepare for possible full site evacuation

On this example, inputs from the sensors are directly used by the control room operator and the control room operator output is what inputs the site manager. The application of this model shows the presence of a distributed knowledge across the system and a communication between the agents based on information rather than models. This communication between the agents based on information joins with the notion of Situation Awareness (SA) as related to information that is define in the engineering view of situation awareness. At the same time the use of the three-level definition of SA from the psychological point of view highlights the importance of human cognition.

This point of view seems to consider both the view of SA for human and for technical systems and thus provides, in my opinion, the most accurate way to represent systemic

situation awareness. It makes it a tool for studying interactions between agents in a system. This approach of situation awareness is part of a sociotechnical analysis paradigm called event-based analysis of systemic team-work (Stanton et al. 2005; Walker et al. 2006) that focuses on modeling tasks, social and knowledge networks and the interconnection between networks. These networks of information elements are activated according to the tasks to be performed. This representation integrates the notion of evolution of the situation as a major role leading to the necessity of a constant evolution of the agent's situation awareness. This means that the situational awareness of an agent consists in providing the right information to the right agent at the right time for the task at hand.

1.2.3 Improving human situation awareness

Improving human situation awareness can be performed from several perspectives. Looking at studies aimed at improving situation awareness from an engineering perspective, it appears that improvement can be performed in several ways.

Usbeck (Usbeck et al. 2015) worked on a **shared awareness** tool enabling to contextualize information and to share situation elements between users. This mapping application enables users to provide element of the situation to their teammates to share their SA. This solution aims at supporting SA of users in the situation as well as people outside of the situation by making more elements of the situation available to the decision maker.

Following a similar path, Herfort (Herfort et al. 2014) proposed to work on using information from sources outside the decision-maker direct *environment* to multiply situation elements available to the decision-maker. His study proposed to use information from social media to provide emergency response teams with more information related to the faced situation. This solution proposes to find and select information related to the problem faced throughout social medias and to provide that information to the user. This solution aims at using the shared SA paradigm to provide SA to users based on other users SA.

These two previous studies have shown that the use of information about the situation from multiple sources can be used to improve SA of both users in the situation or outside the situation. However, this may be useless or even deteriorate the user's SA if not applied correctly. Providing relevant information is important to ensure SA and failing to do so can lead to dangerous decisions (Nijhoff 2005). Three main problems can be considered when faced with the addition of information:

- Provided information can be irrelevant to the user goal,
- The multiplicity of provided information might cause user cognitive overload,
- The information can be divergent, contradictory, or partial and provide wrong SA to the user.

Because SA requirements may differ depending on the decision maker, it appears that improving SA is not just about providing information but also about providing the right information. The studies presented above as well as others (Bolstad et al. 2005; de Walle et al. 2017), have understood the limitations and thus have proposed solutions to ensure the quality of the provided information.

Herfort's proposed solution is to use machine learning algorithms to select situation-related information from online discussions. Based on a geographical and phenomena oriented matching algorithm, the tool provides information to emergency teams. This allows uninformed sources to be used to provide related information, as the knowledge is contained in the tool. While this limits the information overdose that could result from using a large number of information sources, it does not prevent from false information from being provided and users from providing too much information.

A solution proposed by Bolstad (Bolstad et al. 2005) aims to ensure that information is shared by users who know the SA requirements of their teammates. Cross-training ensures that the person sharing the information knows the needs of their teammates. This solution aims at teaching users about the roles and needs of other users. Once this knowledge is acquired, information can be shared with users based on their needs and ensure that related information is provided. However, this solution relies on team members being careful not to provide too much information to their teammates.

In a study on improving SA for crisis response teams, Van de Walle (de Walle et al. 2017) proposed two solutions to address the challenges of multiple information in the form of enhanced information and centralized information processing and distribution.

In the first case, the information is provided to the decision maker with an additional summary of the information. This solution proposes to provide the decision maker with predefined situation analysis to reduce its need to process the SA levels. This solution is based on the capabilities of information systems to provide more richness to the information in the form of summaries, averages, comparisons for example. This solution aims at providing the user with more information without requiring more cognitive processing resources.

In the second case, the information is centralized to ensure coordination. The use of a central coordinator is intended to ensure that information is shared with decision-makers according to their SA requirements. This team member receives all information and redistribute it to its other team members. This solution ensures that only the necessary information reaches the decision-maker but relies on the SA and cognitive abilities of one member of the team.

The solution presented in this section was intended to ensure that the information is correct and available to the user in a manageable amount. However, the source of the

information varies from one user involved in another situation to specifically defined tools.

Considering the solution presented to improve human situation awareness, the provision of new situation-related information promotes human situation awareness. Since users have a limited view of the complex systems they are dealing with, other sources of information embedded in the situation can provide information from their perspective. This solution highlighted the need to use different sources to provide a more complete view of the situation to humans in or outside the situation. However, as we have shown, the quality of information is predominant over the quantity of information. Therefore, solutions to ensure information quality seem necessary to improve human situation awareness.

1.2.4 Evaluating Situation Awareness

Working on situation awareness and working on improving it ask for a need to evaluate it. Multiple situation awareness evaluation techniques have emerged in different domains to answer this need for situation awareness rating. Five situation awareness assessment techniques are presented and discussed in this section.

1.2.4.1 Situation Awareness Global Assessment Technique

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 specific point in time and provides queries to the user.

These queries are defined to reflect on the three levels of situation awareness: (1) perception of elements, (2) comprehension of the situation and (3) projection of the situation. SAGAT queries are based on a previously conducted situation awareness requirement analysis (Mica R Endsley et al. 2003). The queries are categorical to minimize the user's workload and allow for quick responses. The results from this assessment are statistical responses that provide insight into the user's ability to perceive, comprehend and project a situation.

1.2.4.2 Direct Questioning Technique

The Direct Questioning Technique (DQT) is a proclaimed methodology derived from SAGAT (Stanners and French 2005). This technique uses questions to evaluate the user Situation Awareness during the tests.

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 6 verbally asked questions.

Based on the answers, the results are evaluated, and a SA score is defined.

I.2.4.3 Situation Awareness Control Room Inventory

The Situation Awareness Control Room Inventory (SACRI) is another evaluation method derived from SAGAT (Hogg et al. 1995), focusing on control room alarm management. This technique is based on a set of twelve questions during simulator freeze. The questions are defined in agreement with domain experts and mainly concern process parameters and displayed information.

These questions were randomly selected and offered to the user by the interface. The SACRI questions are scheduled to be administered during a set of scenarios lasting at least 30 minutes. As with SAGAT, scores are defined based on a comparison with the actual state of the situation at the time of the freeze.

I.2.4.4 SALSAS

The SALSAS SA evaluation method is the German translation of "Measuring Situation Awareness of Area Controllers within the Context of Automation" and aims at providing a more appropriate evaluation technique than SAGAT for future Air Traffic Management systems (Haus and Eyferth 2003).

SALSAS is a query-based method that uses freeze like the SAGAT. However, it differs from SAGAT as:

- An expert is asked to score the replays of the simulation to weight the relevance of the question asked.
- The evaluation is performed in a single stage to eliminate the dependability of the element in several steps.
- The set of question is asked to the user to collect more data in a limited time of interruption.

I.2.4.5 The Situation Awareness Rating Technique

The Situation Awareness Rating Technique (SART) (Taylor 1990) is a self-evaluation method. This subjective rating technique was developed based on general constructs that pilots identified as necessary for pilot situation awareness.

These constructs are then clustered to extract ten global constructs that define situation awareness. Experimentations with these constructs proved to show significance for situation awareness qualification for nine of the constructs (see Figure I-7). These nine global constructs formed the basis of the situation awareness rating technique (SART).

SITUATION AWARENESS RATING TECHNIQUE (SART; Taylor, 1990)

Instability of Situation
How changeable is the situation? Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?

1 2 3 4 5 6 7

Complexity of Situation
How complicated is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

1 2 3 4 5 6 7

Variability of Situation
How many variables are changing within the situation? Are there a large number of factors varying (High) or are there very few variables changing (Low)?

1 2 3 4 5 6 7

Arousal
How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

1 2 3 4 5 6 7

Concentration of Attention
How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focussed on only one (Low)?

1 2 3 4 5 6 7

Division of Attention
How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (High) or focussed on only one (Low)?

1 2 3 4 5 6 7

Spare Mental Capacity
How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?

1 2 3 4 5 6 7

Information Quantity
How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?

1 2 3 4 5 6 7

Familiarity with Situation
How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

1 2 3 4 5 6 7

Figure I-7: Situation awareness rating technique questionnaire.

Comparing the ratings for each construct to awaited results enable to identify the user situation awareness during a situation.

I.2.4.6 Synthesis

There are many other SA assessment methods derived from SAGAT (Neal et al. 2000) or combining different techniques (Burns et al. 2008) that have been implemented. However, two different categories of SA evaluation methods emerge from the literature review: (1) Freeze query-based techniques and (2) subjective self-report.

Both type of techniques can be used to assess situation awareness. However, as previously shown in a comparative study (Endsley et al. 1998), the differences between the two types of techniques will help guide the choice of which type to use.

With respect to the implementation of these techniques, while tests with SAGAT showed no impact of screen freezing on the user's situation awareness, and SALSA was successfully in reducing the time required for freezing, this solution requires extracting the user from the simulation and repeating the process to compare state of the SA. From a human perspective, and in the presence of moderately realistic simulations, disruption of the user's participation in the simulation should be avoided, if possible, to ensure continuous recording of activity. Moreover, this technique must be implemented in a dedicated simulator, either to freeze the simulator like in DQT, or to ask the question through the interface as in SAGAT or SALSA. The SART query, on the other hand, can be added at the end of a scenario in an experimental protocol. The implementation of SART seems to be much easier than that of SAGAT, especially in terms of prototype development time.

Looking at the results extracted from both type of techniques, we find that SART is related to the user's confidence level in situation awareness as well as subjective performance. Conversely, SAGAT-like techniques provide an objective assessment of quality based on responses to specific queries against the baseline. Therefore, SAGAT-like techniques have shown more promising results in obtaining a complete objective picture of the user's situation awareness at specific point in the test. SART, on the other hand, considers users as experts and shows the variation in situation awareness based on users' subjective evaluations.

1.3 Human decision-making support systems

As noted earlier in section 1.2, decision-making, related to complex systems, is a complex task in itself. If one considers decision making as a human process beginning with the identification of a situation (Mintzberg et al. 1976), it has been shown that situation awareness plays an important role in ensuring a correct decision (Endsley 1995). As illustrated in section 1.2.3, from the engineering perspective, improving human decision making is achieved using tools. This section dives into the concept of **Decision Support Systems (DSS)** and more specifically on **Situation Awareness Support Systems (SASS)**.

1.3.1 Decision support systems

Technology systems called decision support systems (DSS) support humans in their ability to make correct decisions. DSS is a concept proposed by Gorry and Scott Morton (1971) and is defined as "a system that supports any managerial activity in semi-structured decisions" (Gorry and Scott Morton 1971). Decision support systems are not intended to solve the problem faced by the decision maker but rather focus on improving the effectiveness of the decision maker (Arnott and Pervan 2005).

The field of decision support systems is composed of different types of DSS that are based on different philosophies applied to different technologies. The Figure I-8 shows a representation of the evolution of the field along the years as proposed by Arnott and Pervan (Arnott and Pervan 2005).

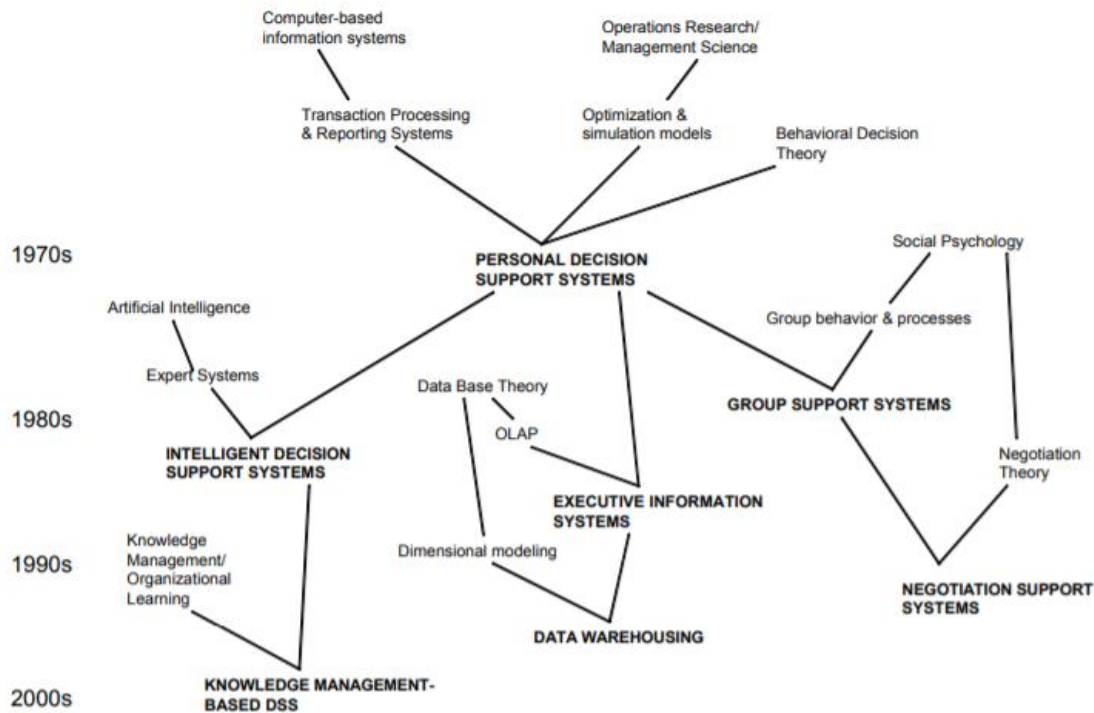


Figure I-8: The evolution of the Decision Support systems field (Arnott and Pervan 2005).

Personal DSSs are developed for a single user and a single decision-making task, such as an analysis generator. This type of DSS developed with the evolution of computers and was introduced at all levels of management as the technology cost decreased. This principle is still in use in today's industry under the term of analytics. This type of DSS can be found in the oil-and-gas industry in the form of the production charts generator that allows management to make production-related decisions for example.

Group Support Systems, at the opposite of personal DSS, aim at supporting a group of decision makers. It is defined as "a set of software, hardware, and language components and procedures that support a group of people engaged in a decision-related meeting" (Huber 1984). Group support systems are systems providing analytics and enabling sharing those through meeting communication tools that can be used during crisis management. They are used to assemble teams of experts from different places and enables them to work simultaneously on the same problem. Such DSS can be found being used in the oil-and-gas domain in crisis rooms where experts are assembled to look at a critical situation and provide a solution to the problem.

Negotiation support systems were developed to support group decision making but with a focus on facilitating negotiations. They focus on the specifics of the bargaining and social choice theories (Arnott and Pervan 2005). Two types of negotiation support systems can be defined. On one hand, **problems-oriented systems** focus on supporting specific problem types. On the other hand, **process-oriented systems** focus on general support for negotiations.

Intelligent DSS (IDSS) are DSS to which the artificial intelligence has been applied (Bidgoli 1998). First IDSS used rule-based systems to provide support to the decision maker. It evolved with the technology and was adapted to neural networks, genetic algorithms and fuzzy logic (Turban, Aronson, and Liang 2005). However, if artificial intelligence is used to find solutions, IDSS don't focus on providing solutions for humans but on providing a support to a human decision maker to make the solutions. An example of such support system in the oil-and-gas would be a system that would investigate past decision-making report to provide information as to which solutions were made and how they solved the situation.

Executive Information systems are data oriented and provide a decision maker with a picture of the organization being managed. They operate on the critical success factor principle (Rockart 1979) and provide the decision maker with values to evaluate the success of the organization. In case of deviations of the values, the manager can work on improving the organization based on the provided information. An example of such a system in the oil-and-gas industry could be used to compare sites with each other in terms of performance and allow decisions to be made to optimize overall production.

Data Warehouses are coming from Executive information systems and the need for large data bases able to provide decision maker with information (Cooper et al. 2000). They usually are used to provide data to other DSS. They use data classification to allow the decision maker to search for the data needed to support their decision. An example of such a system in the oil-and-gas domain is the experience feedback internal system. This system records experience feedback and allows users to search for information through its data classification.

Knowledge management-based DSS focus on managing organizations knowledge and use it to support decision makers. It needs to store knowledge and, as an evolution for IDSS, uses artificial intelligence to articulate this knowledge to support decision makers. An example of such system in the oil-and-gas domain can be found in the maintenance activities as it provides users with knowledge of the past experiences to support the decision maker in his diagnosis.

Some of DSSs types have evolved over the years. Many other types of DSSs can be defined as they focus on specific concepts and methods to support human decision makers. However, as demonstrated in the previous section, situation

awareness is critical for the decision-making process in the case of complex system management. Therefore, the next section focuses on specific DSS that aims to support the decision maker situation awareness.

I.3.2 Focus on situation awareness

This study has been positioned on decision support by ensuring a correct situational awareness for decision making. As shown in section I.2.2, situational awareness can be both seen from a human or technological point of view. From this perspective, it appears that, when viewed from a technological point of view can be supported by systems in the manner as for Decision Support Systems (DSS). Such systems are called Situation Awareness Support Systems (SASS). Like the concept of decision support systems, different support systems to support situational awareness have been created.

I.3.2.1 Modeling situation

Feng (Feng, Teng, and Tan 2009) proposed modeling the situation to provide a picture of the situation to the user through DSS. Such support systems, also called **Context-aware Decision Support Systems** (CaDSS), use models of the situation and rules based on expert knowledge to provide features of the situation to the user. These provided elements are considered as an aid to situation awareness.

This type of SASS is found in the oil-and-gas industry in the form of alarm maps used by control room operators to understand where alarms are located and what their status is.

CaDSS has its roots in the computational view of situational awareness (see section I.2.2.2) by asserting that a model of the situation provides situational awareness.

It can be argued that this view of situational awareness focuses only on the provision of elements but does not consider how the user will react and use these elements. It does not consider the human cognitive acquisition phenomenon of situation awareness.

I.3.2.2 Modeling situation through multiple users

Krytska et al. (Krytska, Skarga-Bandurova, and Velykzhanin 2017) and Wallenius (Wallenius 2004) proposed to use several user inputs to model a current situation at different levels and support the user. This model of the situation can then be presented to the user to support his/her situation awareness. Once the situation is modeled, a set of rules can be used to advise the user and support his/her decision making.

This SASS considers the human factor perspective of situational awareness and the multiplicity of tasks to be performed by humans to provided selective situational awareness to each agent of the system.

Such a SASS can be found in the military domain in the form of tactical maps that allow deployed military officers or base supervisors to provide other users with their own elements of the situation from their SA.

However, while this SASS tailors the information to be displayed to the needs of the user by using filters and information selection capabilities, it does not propose to support the cognitive factors of the human situation awareness process. Again, the information must be processed by the decision maker and no cognitive support is offered.

1.3.2.3 Modeling situation through critical elements

Naderpour and Lu (Naderpour and Lu 2013) and Chandra et al. (Chandra, Krovi, and Rajagopala 2008) proposed using a set of critical environment elements extracted from a task analysis and performing a risk analysis to ensure first level (perception) of situation awareness and provide support for the second (comprehension) and third (projection) level of situation awareness. Focusing on the objective of operator management of hazardous situations, the study proposes to classify risks and project situations to provide support to the second (comprehension) and third (projection) levels of operator situation awareness.

This SASS considers the cognitive model of situational awareness and proposes comprehending and projecting the elements of the situation to support the human cognitive process.

Such SASS can be found in the military domain in the form of tactical maps that provide information about the threat level of the situation element.

Such SASS provides support to all levels of human situation awareness but could be improved to take into account teamwork around the system to perform team-based decision-making tasks.

1.3.2.4 Synthesis

The SASS concept relies on a situation model to provide a first level of situation awareness to users. This model is composed of goal-oriented information that is used collectively to provide a complete representation of the situation. The data provided for the situation model can come from a variety of sources, from technological systems or human beings that are part of the situation, to technological systems or human beings that are not involved in the situation.

In addition to this situation model, knowledge is used to analyze the situation, extract goal-oriented information and provide it to users. This information is then used to help the user understand the situation, thus achieving the second level of situation awareness. It is also suggested to use algorithms to predict the evolution of situations to support the third level of situation awareness.

Based on the presented concepts of SASS, no SASS is built to provide a global support of situation awareness. SASS are preferred to be defined to support specific parts of human situation awareness depending on the point of view on the domain.

In this study, we aim at defining a control room tool considering the human factors definition of situation awareness. Such a system should therefore be able to provide a model of the agent in the environment to support the first level of situation awareness in order to contextualize information. In addition, this tool should use integrated information and knowledge management to the second and third levels of situational awareness. This will allow the tool to support the second and third levels as well. To implement such a tool, it is necessary to look for tool concepts that enable both reality modeling, information providing and knowledge management.

1.3.3 The case of the digital twin

Complex systems are difficult to understand, and their behavior is difficult to predict. Managing and making decision on such system is a complex process. After studying this cognitive process, the need for the human decision maker to be aware of the situation of the system was identified as critical element of the success of the process (see section 1.2.2). To support a decision maker in this complex process, tools have been designed with the ability to provide the needed elements at the correct time. Those decision support systems can have different focuses, and this study focuses on supporting decision makers situational awareness. To help the decision maker with situation awareness, the study of the identified decision support systems has shown that it is necessary for the support system to model the physical system to be managed in its environment and provide the user with extracted information and knowledge.

Such requirements for a situation awareness support system correspond with the **digital twin** (DT) concept. A concept study has been performed to ensure DT ability to support situation awareness. This study is presented in this section.

1.3.3.1 Digital Twin definition

Many different definitions emerged along the years to define the **digital twin** concept. First defined as a perfect Product Lifecycle Management (PLM) tool (Grieves 2014), NASA (National Aeronautics and Space Administration,) formalized the concept as "an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that uses the best available structural models, sensors update to mirror the life of its corresponding flying twin" (Glaessgen and Stargel 2012).

While this first definition is very specific to the case of flying vehicles, a more general definition of the concept of digital twin as composed of "a physical products in Real Space, virtual products in Virtual Space, and the connections of data and information that ties the virtual and real products together" was proposed by Grieves (2014). This simplest definition is refined depending on the domains point of view:

- From the point of view of **cyber-physical systems**, the digital twin concept “posits that the flow of data, process and decision is captured in a software avatar that mimics the operation” (Datta 2016).
- From the point of view of **autonomous system**, the digital twin concept is summarized as a “very realistic models of the current state of the process and their own behavior in interaction with their environment in the real world” (Rosen et al. 2015).
- In the manufacturing domain, the digital twin is defined as “a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration” (Negri, Fumagalli, and Macchi 2017).
- From the point of view of the system engineering community it is “a dynamic representation of a physical system [...] continuously updated with the latter’s performance, maintenance, and health status data throughout the physical system’s life cycle” (Madni, Madni, and Lucero 2019).

Looking at the multiplicity of definitions for concept of a digital twin, it is important to highlight the following concepts difference (Wright and Davidson 2020) (see Figure I-9) that are (1) **the digital model**, (2) the digital shadow and (3) the digital twin (Kritzinger et al. 2018).

- The **digital model** is a digital representation of a physical system (existing or to be). This representation is only representative of the system thanks to manual updating. A change in state from the physical system or the digital model as no effect on the other. The digital model can be a mathematical model, a simulation driven model, a process model, or any other model of the system.
- The **digital shadow** is an evolution of the digital model in which the digital system model is linked to the physical system. This link is made possible using sensors that provide data from the physical system. Therefore, any status changes on the physical system are updated on the digital system but not vice versa.
- The **digital twin** can be seen as an evolution of the digital shadow where both the digital and physical system are linked through a data flow. Therefore, like in the digital shadow concept, the physical system status is updated on the digital system but moreover the digital system can be acted upon to affect the physical system.

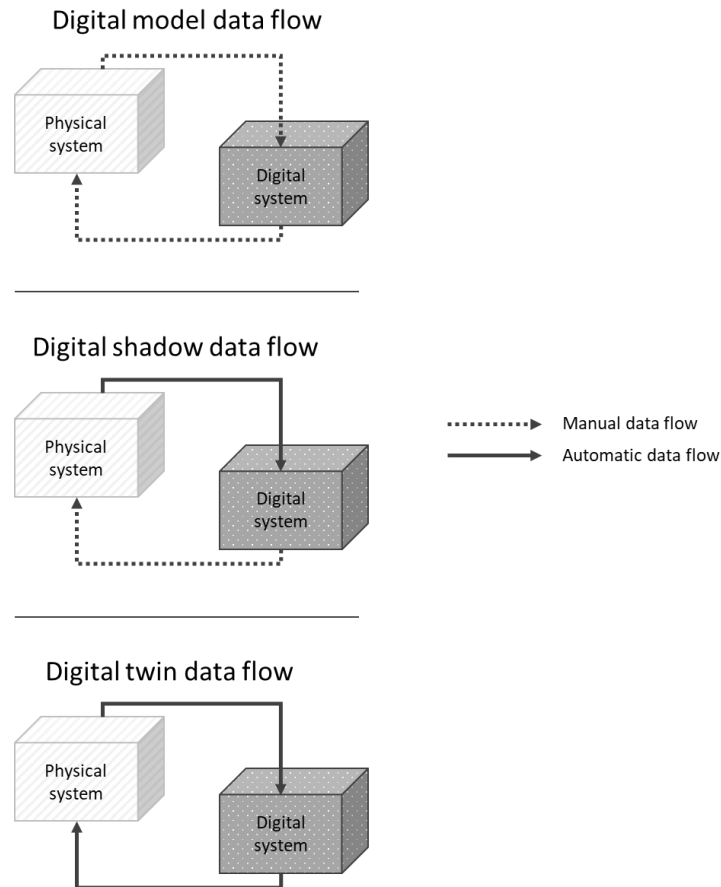


Figure I-9: Data flow in a Digital Model, Digital Shadow and Digital Twin (Kritzinger et al. 2018).

Working on the concept of the digital twin, as a representation of a physical system with bidirectional data flow, the multitude of more specific definitions makes it difficult to define such a holistic concept. By examining the definitions proposed in the literature, some critical elements of the concept can be brought together so that the overall paradigm of the digital twin can be highlighted:

- The need for the digital twin to be the model of a physical system has been established (Tuegel et al. 2011). This is part of the differences between a digital model, that can be a system to be, and a digital twin.
- The representation of the system might not be enough, and the capture of its environment is needed to ensure a global, in context, image of the system.
- The data flow between the physical model and the virtual model as to be a two-way flow. This element of the digital twin is what difference it from a digital model for example. This connection can be performed using sensors and actuators (Rosen et al. 2015). This makes it a tool for system management.
- This two-way data flow is representative of the dynamic aspect of the digital twin. A digital twin is an image of its physical twin in its current state.

- If the digital twin represents the system at its current state, it also uses simulation abilities to forecast future states and, thus, is able to represent future states of the system (Morton et al. 2009).

Following the states of its physical twin, the digital twin can store every past state of the system. Combined with its ability to represent the current states and predict future states, it allows the system to be represented throughout its entire life cycle (Stojanovic et al. 2021).

- System models can be seen from different perspectives. The digital twin aiming to provide a holistic representation of the system must be able to handle many data sources and formats and make them an interconnected data flow. This allows the digital twin to provide multiscale models of the system.
- Finally, the data management capability of the digital twin allows information to be extracted from the data and even knowledge to be generated, giving the user the ability to manage the represented system and assist in decision making (Min et al. 2019).

A global definition of the digital twin paradigm emerged from a "Rapid Technology Assessment" study performed by the UK Government Office for Science in March 2021 stating that *"a digital twin is a collection of one or more computational representations of a physical asset, entity or process with a flow of real-time data from installed sensors on the physical asset. A digital twin can be used to monitor and evaluate the performance of the physical asset across its lifecycle as part of a dynamic process with the ability to remotely interact with or control the physical asset."*¹³. If this definition corresponds to most critical points defined previously, it does not focus on the uses of the digital twin and tend to forget about its internal ability to generate knowledge and to partially (if not autonomously) manage the system. Moreover, the representation of the system environment is not mentioned in this definition.

I proposed to define the digital twin concept 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 action on that system"* (Camara Dit Pinto et al. 2021). This definition aim at assembling all the define critical elements of the digital twin in a global definition without restricting it to specific technologies or uses. Such definition does not encapsulate the digital twin concept in term of its role in system management. Looking to use the digital twin concept to support decision making, understanding its ability to provide the user with system management ability is crucial. The roles of such tool in terms of system management are therefore a good representation of its ability to support system management. If the

¹³ <https://dmf-lab.co.uk/blog/to-twin-or-not-twin-and-when-is-a-twin-not-a-twin/> (accessed last 25/07/2022)

digital twin paradigm aims to support decision making in a general way, the role of the digital twin as evolved through its development. These roles are presented in the next section.

I.3.3.2 Digital Twin roles

If the digital twin concept history as inspired several formal definitions, it can also be defined by the evolution of its role in term of systems management. Four main roles of the digital twin have been identified by Negri et al. (Negri et al. 2017).

Health monitoring

The digital twin concept can be defined to mimic a real system and monitor its health (Glaessgen and Stargel 2012). Such digital twin uses sensors to update critical life points of the system. These models therefore propose a current partial image of the system. Those digital twins were first introduced by NASA on space vehicle and can still be found currently for representing assembly line health status for example.

Such digital twin provides representation of the current state of the system for decision maker to act on the physical system to manage the system based on this image (see Figure I-10).

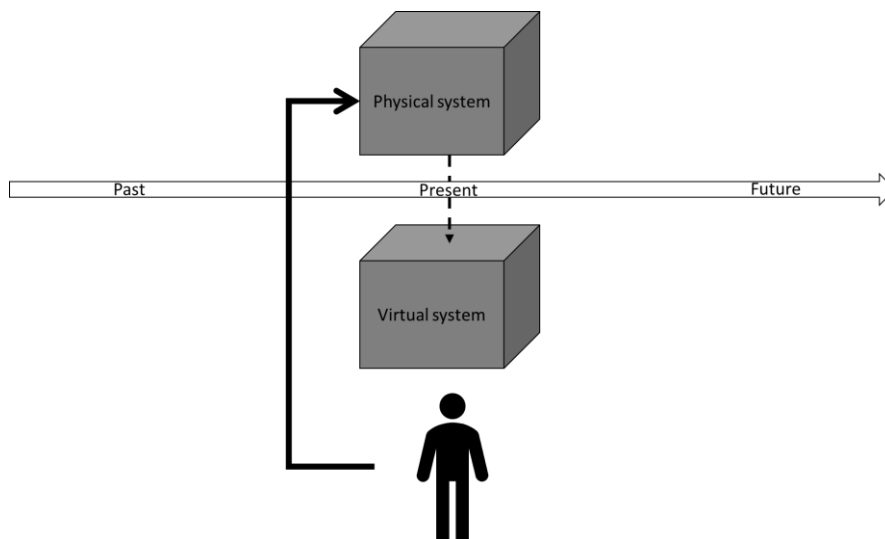


Figure I-10: Model of digital twin for system monitoring.

Simulation and prediction

The role of the digital twin can be defined to enable simulation and prediction (Datta 2016). Thanks to the evolution of digital models, the digital twin become able to use digital models' abilities to represent but also simulate states of the system. This enables to study systems along its life cycle and predict behavior. Such systems can be found on engines for predictive maintenance use for example.

Such digital twin provides a virtual image of the future state of the system. However, due to computation time limitations of such models at the time, users could only obtain

information useful for long term decision-making (see Figure I-11). Even if simulation capabilities have evolved to provide faster results, the aim of these digital twins remained focused on long term decision making.

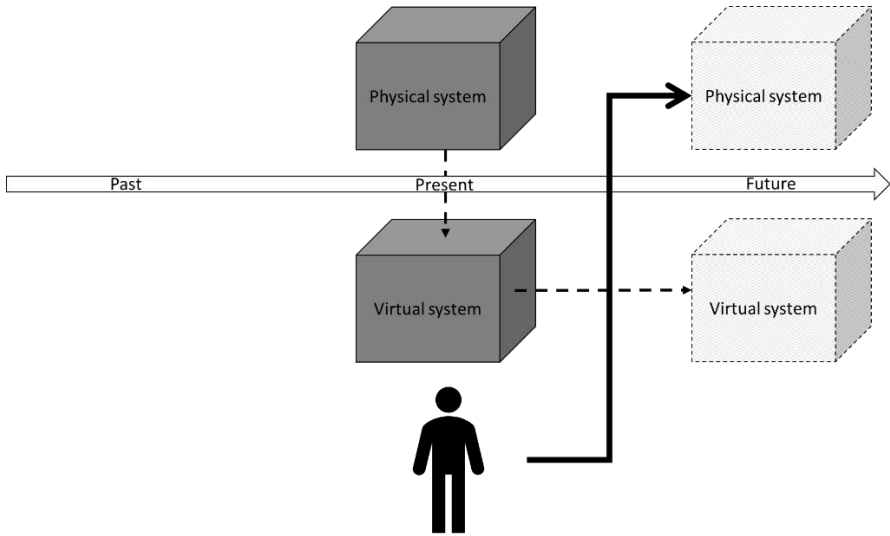


Figure I-11: Model of digital twin with simulation abilities.

A posteriori optimization

With the development of machine learning abilities and its implementation to the digital twin concept, its role evolved to enable a posteriori system optimization (Brenner and Hummel 2017). The digital twin ability to model, monitor and simulate coupled with the ability to use machine learning to explore stored data, enabled to optimize the systems based on previous monitored data and future predictions. Such digital twin is used for more precise predictive maintenance uses as well as plants optimization for example.

Such digital twin provides to the user knowledge from the past to support its decision. However, the data processing time made it a tool for optimizing the system for its future states (see Figure I-12).

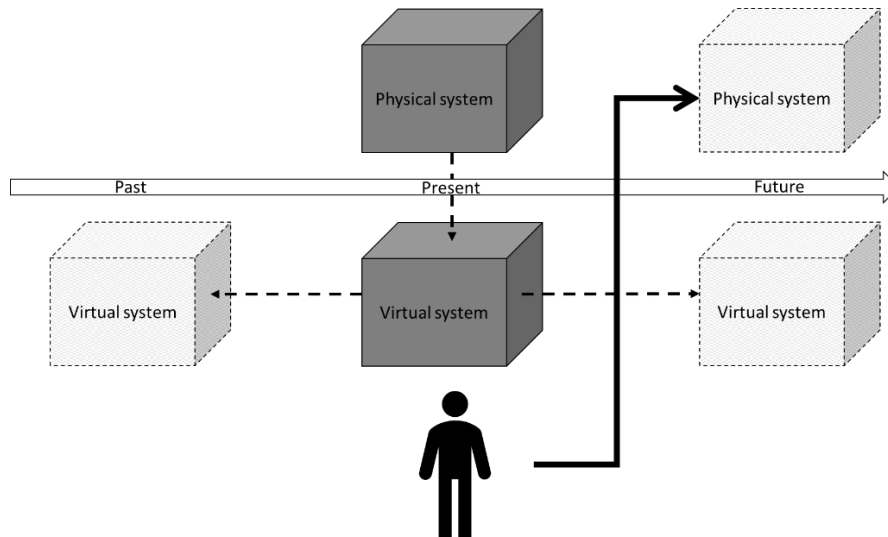


Figure I-12: Model of digital twin for posteriori optimization.

Real time optimization

The augmentation of computational power has enabled real time -or near real time- decision making support (Min et al. 2019). The ability to model reality, predict, and optimize based on the past at a near real time speed enabled to implement decision model and support decision making in real time.

Such digital twin provides information and knowledge to a user in real time for him to manage the system in real time (see Figure I-13).

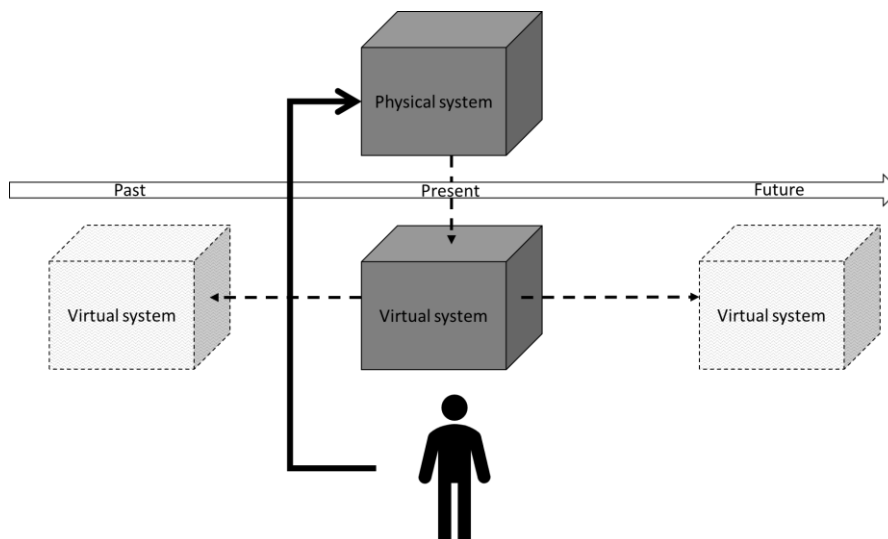


Figure I-13: Model of digital twin for real time management.

Synthesis

Looking at the roles of the digital twins introduced in this section, their abilities can be summarized in the Table I-2.

Table I-2 Digital twin roles abilities summary

Roles	Past	Real time	Future
Health monitoring	No	Yes	No
Simulation and prediction	No	No	Yes
A posteriori optimization	Yes	No	Yes
Real time optimization	Yes	Yes	Yes

This study focuses on making decision upon a system in real time. Looking at the classification exposed in this section, only two digital twin types enable such ability in a human decision maker: (1) a monitoring digital twin or (2) a real time processing digital twin.

A monitoring digital twin would provide a real time representation of the system enabling to provide health status to the decision maker. However, such digital twin is limited in term of processed data as their ability is limited to real time monitoring.

A real-time processing digital twin could provide the user with more data, information and knowledge to inform its decision. However, as discussed in the situation awareness section, too much data or information can have a negative effect on a decision maker situation awareness.

Therefore, if it is preferable to work on real-time digital twin, a careful attention will be put on ensuring to support the decision maker and not neglect its cognitive needs.

I.3.3.3 Digital twin levels

If the digital twin concept can be studied in term of its roles in the management of systems, the authors of (Madni et al. 2019) proposed a four-level categorization of the digital twin maturity. The maturity is evaluated from the point of view of the model-based system engineering community and evaluates the digital twin concept in term of:

- Sophistication of the model,
- Presence of a physical twin,
- Data acquisition from the physical twin,
- Support of the operator preferences using machine learning abilities,
- Consideration of the system and its environment using machine learning abilities.

This classification defines four level of maturity for the digital twin concept.

Pre-Digital Twin

Pre-Digital twin or digital model: this first level DT is a virtual prototype mostly found in PLM tools. These pre-DTs are used to support decision making during the design phase. These pre-digital twins are categorized by the absence of physical twin at the beginning of the digital twin life cycle.

Example of such first level digital twin can be found in the designing of the Dassault Falcon 7x that was performed entirely digitally and lived as a first level digital twin before the physical twin creation¹⁴.

Digital Twin

Digital twin: this second level DT is a virtual representation of a real system using models with the ability to collect information on the system using sensors. These DTs are used to monitor performance, health, and maintenance data through batch updates and store the data along the life cycle. The data are used to update the system model and to make high level decision. Such digital twin has bidirectional interactions and can therefore act on the physical model based on the data collected. Such digital twin can also be used to test what-if scenarios and make decision and update the system based on the scenarios results.

Second level digital twins are seen in engine monitoring, production line optimization applications. A production line would provide health status through batch update and optimize workflow based on the provided data.

Adaptative Digital Twin

Adaptive digital twin: this third level DT uses real time updates and machine learning algorithms to adapt interface to the user preferences. The user preferences are captured supervised machine learning algorithms. The captured preferences are then used to adapt the user interface. The models represented on the interface are also using real-time monitoring to enable real-time decision making.

Adaptive digital twins are used for installation monitoring where adapting the interface from normal state monitoring to urgent state monitoring could be performed based on user needs.

Intelligent Digital Twin

Intelligent digital twin: this fourth level DT uses the same abilities of a third level adaptive digital twin but also uses high-level abilities to consider system environment and extract knowledge for the real twin monitoring through unsupervised machine learning.

¹⁴ <https://www.3ds.com/fr/newsroom/press-releases/dassault-aviation-and-dassault-systemes-make-industry-history-falcon-7x-jet-becomes-first-aircraft-entirely-developed-virtual-platform> (consulted last 03/08/2022)

Intelligent digital twins use unsupervised machine learning to analyse the environment and, thanks to a high degree of autonomy, manage the physical system. At this level, the digital twin has a high degree of autonomy.

Synthesis

Looking at pre-digital twin, such digital model is not considered in this study. The lack of a physical system to be managed implies it is not a digital twin even if it was its origin.

Digital twin can be considered as the base to provide information to a decision maker. However, it does not support the decision maker in a real time decision ability as the data are not updated in real time. Such level of digital twin would therefore not be adapted for the aim of this study.

Adaptive digital twin sees the apparition of both real time updates and a focus on presenting information to the decision maker in a coherent way. Adaptive digital twins are therefore the first level of maturity to be considered in this study. Its abilities make it able to provide real time information to a decision maker and even to support this information presentation through an adaptive interface.

Intelligent digital twin conserves the ability to provide real time information to a decision maker but can provide knowledge extracted from the system and its environment to a decision maker. Providing such knowledge to a decision maker can support its decision ability more efficiently (if provided by taking in consideration the decision-making cognitive phenomenon).

Table I-3 Levels of the digital (Madni et al. 2019)

Level	Model Sophistication	Physical twin	Data Acquisition from Physical Twin	Machine learning (operator preferences)	Machine learning (System/Environment)
1 Pre-Digital Twin	Virtual system model with emphasis on technology/technical-risk mitigation	Does not exist	Not applicable	No	No
2 Digital Twin	Virtual system model of the physical twin	Exists	Performance, health status, maintenance; batch updates	No	No
3 Adaptive Digital Twin	Virtual system model of the physical twin with adaptive UI	Exists	Performance, health status, maintenance; real-time updates	Yes	No
4 Intelligent Digital Twin	Virtual system model of the physical twin with adaptive UI and reinforcement learning	Exists	Performance, health status, maintenance, environment; both batch/real-time updates	Yes	Yes

Considering these four levels (see Table I-3) and the aim of this study, using a fourth level digital twin appears as the one with the best ability to support human decision-making. An adaptive digital twin could also, at first, provide some support in terms of information display. However, as seen in the previous sections, supporting situation awareness can be done by information display but information management and knowledge generation is needed to support situation awareness in every possible way. To consider these abilities for future development of a digital twin for supporting situation awareness, this study will tend to reach the fourth level of maturity.

I.4 Supporting Situation Awareness using a Digital Twin

As noted earlier (see section I.3.3), the capabilities of a digital twin can be used as a DSS. Furthermore, the concept of a digital twin highlights capabilities that, when they reach a certain level of maturity, can be used to support situation awareness.

Digital twins are complex systems by nature as they aim at representing a physical system and its environment in a holistic way. As explained in the global view of complex systems, such a system can be decomposed into components and the interaction between the components and its environment studied to give a global view of the system.

This approach is followed in the next sections.

I.4.1 The components of a digital twin for Situation Awareness support

The digital twin concept was first defined by the presence of three components (Grieves 2014) that are a physical part, a virtual part and a flow of data between the two. Taking into consideration the roles defined for the digital twin concept it becomes difficult to represent it using only these three components. To have a better decomposition of such a complex system, a decomposition into 5 main internal components is proposed in this study.

I.4.1.1 The situation model(s)

The situation model is the representation of the situation and can be decomposed into two main models that are (1) the real system model for physical representation (of the current situation) and simulation (of a possible future situation), and (2) the contextual model for the representation of the environment, humans, and equipment surrounding the current situation.

- The real system model represents the system itself in many forms as traditionally integrated in digital twins. This metamodel can be composed of structural model, fluids model, process model, system specifications, expert knowledge model or any other model needed to represent the data.
- The contextual model focuses on enlarging the representation of the system environment. It can include geographical representation of the area, weather

model, nearby systems that could affect or be affected by the system. Adding such model in the digital twin focus on taking into consideration the holistic nature of complex system behavior.

The use of such models in the digital twin enables representation of the current situation, simulation of possible future situations and prediction of the outcomes of these hypothetical situations.

For example, in an oil-and-gas offshore platform, models of the process can enable to represent the current state of the process. This model could simulate its evolution if the process as to be shut down or not and predict the production outcome of the process in each case.

I.4.1.2 The sensor data

The sensor data enables the continuous monitoring of the system and updating the models to fit the representation of the current situation with reality. This component is part of any digital twin reaching the second or more level of maturity (see section I.3.3.3). The sensors placed on the physical system enable to extract specific status of reality as a link between the real-world and the digital world. In the case of real time decision support, the sensors data must be providing real time data to ensure all changes in the situation status are reported to the digital twin model.

For example, in an oil-and-gas offshore platform, pressure sensors are used in separator to provide the pressure value inside the drum and update the process model.

I.4.1.3 The interface

The interface is the component needed for the interaction between the digital model and the user. It provides information and knowledge to the user based on the situation model. The interface can itself be structured in different part to enable the user to interact with different part of the digital twin, provide multiple view of the situation to a user at the same time or provide different view of the situation to different user at the same time. The interface must be implemented following human centered design methodologies to ensure a human adapted set up.

For example, in an oil-and-gas offshore platform, the control room are equipped with multiple monitors that enables the control room operators to have access to the information needed to continuously monitor the platform health.

I.4.1.4 The data management

The data management component allows the orchestration of data flows in all the DT components. This component appears in every digital twin. It can be decomposed in three main sub-components working together: (1) data reduction to summarize data; (2) data selection to elicit specific data when needed; and (3) data processing to elicit general knowledge.

- The data reduction component enables to synthesize and select consistent data according to predefined rules. Those data can then be communicated or stored. With this component, the digital twin converts a data set into more manageable data and information to be reused by other components. For example, the data reduction can enable to synthesize the sensors data that arrives every second into a general value.
- The data selection component enables the digital twin to select data or information following a set of criteria. Such ability is to be used by the user itself under the form of a search into a database or by other components needing access to specific data or information. For example, the data selection enables every sensor that is detecting an anomaly in a list of every sensor on site.
- The data processing component enables to generalize information into knowledge to be stored or used in combination of other components. The technical form of the subcomponents is up to the choice of the digital twin as many forms of algorithms with advantages and constraints are available in the literature.

I.4.1.5 The memory

The memory storing data, information, and knowledge throughout the life cycle of the system. Digital twin's memory component is a technical challenge as data, information and knowledge stored are usually in various formats. The digital twin memory aims at storing physical data that represent the system like pressure value from a sensor, alarm status that are provided through different format. It also aims at storing knowledge under the form of algorithms and rules to be used by other components.

I.4.1.6 The actuators

The actuators are used to act directly on the system. They can be activated by the user itself or internally by the digital twin in case of automatic actions. This component is what makes the digital twin different from a digital shadow. For example, on a control room operating system, actuators take the form of valves controlled by the system to regulate the system. These valves enable the system and the user through it to act on the process.

I.4.2 The interaction of the digital twin components

Each component of the digital twin described above has interactions with one or more other components and/or with the user. These interactions are presented in Figure I-14.

The "physical complex system" is the system to be managed and represented by the digital twin through the situation model component. The structure of the situation model is defined to represent as best a possible the physical complex system with a focus on the system itself and the context it is performing. A processing unit, like an off-shore oil-and-gas platform for example, can therefore be described as being composed of a process and a physical structure. The process will aim at representing

the working process with the related KPIs (Key Performance Indicator) and the structure will aim at representing the physical structure of the unit. The context related to both models can be for example a model of the maintenance information, the site or building layouts, the humans in its proximity, or its local environment (weather information, neighborhood, etc.).

Data from the physical system is collected using sensors. This data will then be processed in the data management component. As explained earlier, this component is composed of three subcomponents that are data reduction, data selection, and data processing components.

Data management is central in the digital twin, as it distributes data to the various other components. It is directly linked to the memory because it allows both to collect data for processing and to store them once acquired or processed. The processed data is then used to feed the situation model.

The interface component can be composed of several views and will be used to display both the situation model or the information required by the users. The log of user interface usage will also provide data to the data management components. This interface component is the link between the user and the digital twin.

The user will use his/her senses to perceive elements of the situation through the interface. As we have seen in the process of acquiring situation awareness (see section I.2.2), the perceived element will be stored in the short-term memory to perform the comprehension process. This process will use elements in the short-term and long-term memory to establish a model of the situation in the working memory. This model will then be projected to define projected situations. These are then used by the user to carry out his/her decision-making process and choose an action to be carried out. Once the process is completed, the experience acquired by the user will be stored in the long-term memory to provide knowledge for future decisions.

The chosen action can be performed with or without the digital twin. In the case of using the digital twin, the actuators will be used to act on the complex physical system. The use of the actuators will also provide data to the data management component that will use or store it for future use.

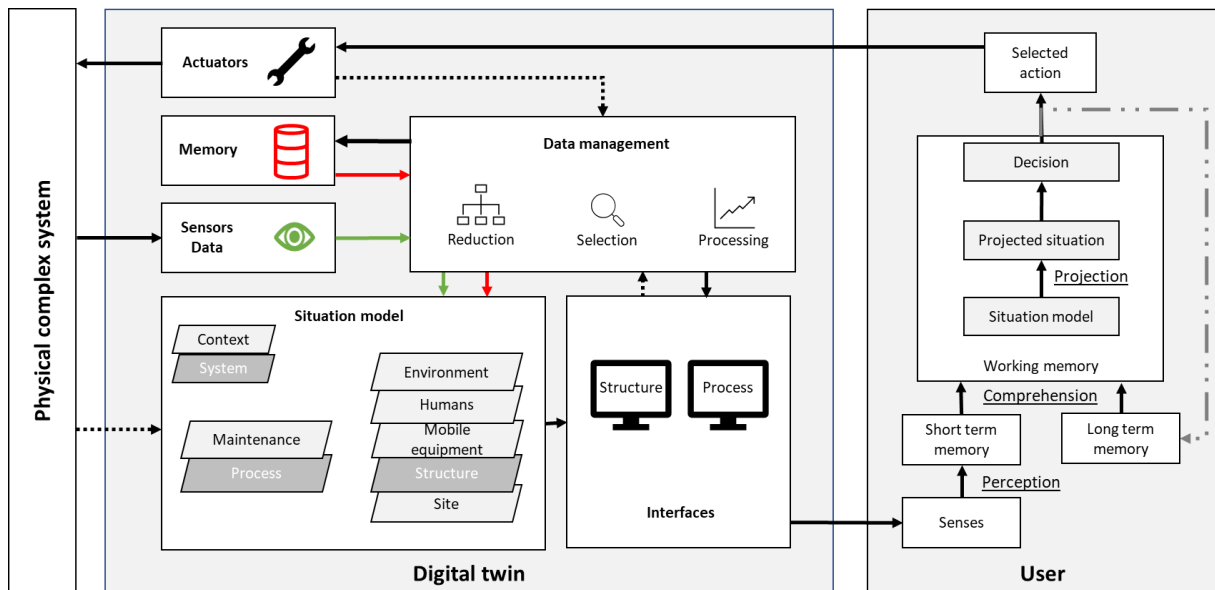


Figure I-14: Digital twin components and situation awareness.

The digital twin model defined in this section highlights the capabilities of the digital twin and how the components work together to enable those capabilities. When related to the user and their process of gaining situation awareness and making decisions, it shows the capabilities of the digital twin to support situation awareness.

I.4.3 Impact of the Digital Twin components on Situation Awareness

The components of the digital twin defined in the last sections have been defined in terms of the capabilities of the digital twin theorized in the literature. Among these digital twin capabilities, the support of situation awareness is what this study focuses on. Following the human factor vision of situation awareness (see section I.2.2.3), the components of the digital twin work together to provide to the DT its own situation awareness.

*Table I-4: Impact of the Digital Twin components on Situation awareness levels.
(Camara Dit Pinto, 2021)*

Digital Twin components	Digital Twin Situation Awareness levels
Real system model	Perception and projection
Contextual model	Perception and projection
Sensor data	Perception
Interface	Perception, comprehension, and projection
Data reduction	Perception
Data selection	Comprehension
Data processing	Comprehension and projection
Memory	Comprehension and projection
Actuators	Comprehension

The real system and the contextual models allow to represent a complete situation and, thus, can be identified as a support for the perception level. Their aim is to represent the situation by modeling specific elements of the reality and provide element needed in the perception process. In addition, the ability for such models to simulate possible future states of the system makes them a support to identify possible projected situations.

The sensors data are a direct link to the system situation as it provides direct data from the reality. They are therefore a support to the perception level of the human situation awareness.

The interface component display information and models to the user. It makes it a crucial component for the user to acquire situation awareness using the digital twin. It can be considered as containing the perception, comprehension, and projection level of the situation awareness.

The data reduction component aims to transform a large amount of heterogeneous data in usable synthetized data. This component of the digital twin can be considered as providing usable element of the situation and supporting the perception level.

The data selection component aims to retrieve and provide selected information among all available information (from current situation or from memories). This ability enables the digital twin to look in a long-term like memory to provide information from it. This process is similar to the one performed by humans to perform the comprehension of the situation (see section I.2.2.1). This shows this component can be used to support the comprehension.

The data processing can transform data and information in a more advance way and could be used to extract correlations or models. These elements characterize the comprehension and projection levels.

The memory component is a major element necessary for the comprehension and projection levels in the human process. Similarly, it can be considered as supporting the same levels in the digital twin.

The actuators enable the user to act on the system. This enables the user to compare the action performed on the system and its reaction to provide comprehension of the element connection to one another.

Example I-11: Example of digital twin.

Taking the example of applying a digital twin to an oil-and-gas off-shore platform control room, the platform should be modeled in the real system contextual model. This model coupled with the sensors data should allow to represent the process to the user and enables to provide the situation element for the user to be perceived. The ability from the model to simulate future possible states by simulating the effect of a valve being closed or simulating gas dispersion should enable the user to see into possible future and supports the projection level.

The data reduction component should enable to highlight general information like a set of pressure values to identify more usable information like the communication mean and provide this information to the user. The data selection component could take the form of a search module in an experience feedback data base. Using this research ability, the user could find similar cases and could formalize a comprehension of the situation based on these past events. The data processing could recognize situations based on critical factors and should provide the user with a comprehension of it. Moreover, it could identify possible futures and support projections based on knowledge contained in the digital twin.

This model, the associated sensors data and the data extracted from the data management component would be presented to the user through the interface. In the case of an oil-and-gas off-shore platform, two distinct interfaces could be used. The process interface should enable to use the process related data like the sensor feedback, the link between the equipment on site or the process simulated future. The structure interface should enable to link sensors data to geographical

information locations and to identify projections of the human movement on site for example.

Conclusion

Complex systems are by nature defined as being difficult to understand on a global scale, with behavior that is difficult to anticipate. Theories have been developed to facilitate their understanding. The theory of aggregate complexity chooses to subdivide complex systems in elements and to study their interactions. If understanding a complex system becomes easier, human still must manage them and their unpredictable behavior makes decision-making difficult.

Considering the decision-making process involved in the management process, humans follow well-defined steps from identifying the situation, designing solutions, evaluating the solutions, and choosing an action to be taken on the system. To support this process, emphasis has been placed on the first step that requires the decision maker to have situational awareness. The situation awareness cognitive phenomenon is defined in three levels: perception, comprehension, and projection. Human factors theories define situation awareness as a concept for both humans and systems.

To support such a phenomenon, a look at the concept of decision support system introduced how systems are used to provide support to human decision maker. These tools are defined for specific uses and use specific capabilities to support humans. Aiming at supporting situation awareness, the need for a model and an ability to manage data emerged as characteristics of the situation awareness support systems.

The digital twin concept meets these characteristics. A study of the concept revealed a multiplicity of definitions dependent on the domain of study. From these definitions, the extracted requirements for the paradigm allowed to propose a global definition of the concept. After examining the roles and maturity levels of digital twins, its ability to support situation awareness have been confirmed.

To use a digital twin to support situation awareness, a more applied definition in five components have been proposed in this study. Following the aggregate complexity theory, the interaction between the components have been defined. The definition of the components and their interaction have finally enabled to define the impact of the component on the digital twin situation awareness.

However, if the definition of the digital twin as a SASS is consistent, a design methodology for such a digital twin for situation awareness must be provided. This design methodology will be explored in the next section.

Part II: Methodology for designing a decision-making tool that supports situation awareness

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Introduction

Managing a complex system is not a trivial task (see part 1 section I.1.3) often because it is difficult to understand and anticipate its behavior. Human operators make decisions to manage system's behavior. The decision-making process, studied in part 1 section I.2.1, involves situation awareness (Endsley 1995). The digital twin concept, defined as *a dynamic representation of a physical system using interconnected data, models, and processes to enable access to knowledge of past, present, and future states to manage action on that system* (see part 1 section I.3.3.1), is considered in this work as a tool to support decision making and situation awareness in the framework of holistic complex system management. However, designing such a tool is not trivial because a digital twin can be considered as a complex system itself. We proposed a decomposition of the digital twin into components based on the aggregate complexity theory (see part 1 section I.1.2.3) and design methodologies for its implementation.

Methodologies have been developed to focus on specific objectives. This study aims to provide support to the decision maker confronted with complex systems. Therefore, we decided to focus on human-centered methodologies for the design of decision support systems, with an emphasis on situation awareness for human decision support. We developed a new methodology, called the Reality Anchor Methodology (RAM).

II.1 Reality anchors

Situation awareness acquisition from humans is usually acquired as being part of the situation. Under a certain condition, situation awareness support systems provide information to users who are embedded in the situation. However, working with complex systems modeled through a digital twin, the user is located remotely from the situation (see I.3.2.2). Therefore, there is a need to "tangibilized" reality through the digital twin. This goal encouraged the definition of the reality anchor concept.

In the case of immersion in the situation, the acquisition of the element of reality is direct using human senses (see Figure II-1).

In the case where one is not integrated into the situation, the acquisition of the element of reality is performed through a model of the situation (see Figure II-1). Complex systems are composed of many sub-systems (see part 1 section I.1.1), this makes them especially challenging to model completely. Therefore, the reality anchors are defined as *useful elements of the situation necessary for humans to enable them to grasp reality and acquire a meaningful situational awareness that supports the decision-making process*. The elicited anchors are supposed to be used as guidelines for modeling the situation in a SASS.

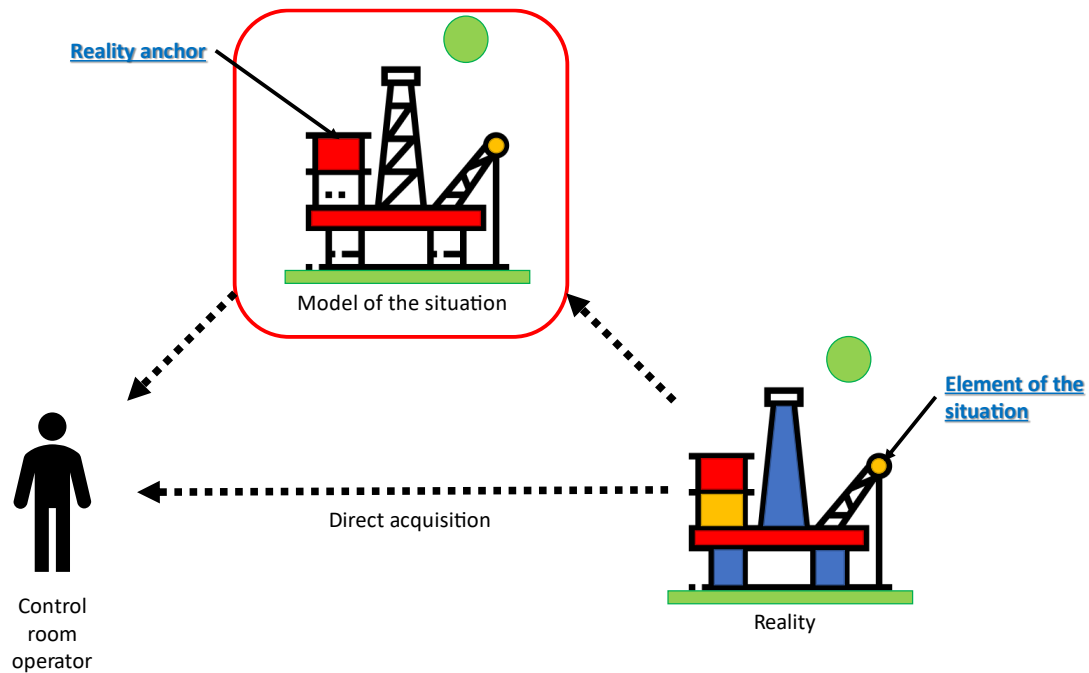


Figure II-1: Element of the situation perception through the use of situation models.

If the concept of reality anchor is now defined, it is now important to focus on designing a system in which implement a model of the situation.

II.2 System design

System design has been studied for many years and several methodologies have been developed. While the earliest writings on design methodologies can be traced back to the 1950s (Zwicky, 1948), it is commonly accepted that the field began with the Design Methods Conference in London in 1962 (Jones and Thornley, 1963). Throughout the history of the field, subfields have been developed to define good practices when designing systems for a specific purpose. Examples of such subfields are:

- Technology-centered design is defined as “a process in which the designers or their clients make design decisions which are imposed on the intended users” (Zoltowski, Oakes, and Cardella 2012).
- User-centered design is defined as “a process and a set of techniques used to create new solutions for the world. Solutions include products, services, environments, organizations, and modes of interaction. The reason this process is called “human-centered” is because it starts with the people we are designing for.” (IDEO 2015)

This study focuses on supporting human decision-making capabilities through the design of a decision support system (DSS). As discussed in the Part I, the choice as been made to support human decision making by designing a digital twin that supports situation awareness, thus ensuring a better human systems integration, based on human-centered methodologies.

II.2.1 Human-centered design

Traditional technology-centered engineering focuses first on the implementation of the technology and assumes that people will adapt to it (Boy 2013). As system complexity increases, user-system interfaces are reduced to an end task, forcing users to adapt to the system (Boy 2020). The increasing complexity of systems has brought these "patches" to their limits, as humans can no longer properly adapt to the system due to its complexity and thus the system becomes unusable.

Conversely, Human-Centered Design (HCD) helps to consider end-users as early as possible in the design phase to ensure the most appropriate technological solutions. This paradigm was born from the recognition of the role of humans in the life cycle of the system, and in particular in the design phase. Methods have been defined to involve users in the system design phase and adapt systems to users. Some key principles ensure this involvement and adaptation to the user (Maguire 2001):

- *Actively involve the users and clearly understand tasks requirements.* Users know the uses of the system and can ensure that the system matches those usages. The involvement of the users will also allow a better acceptance of the system by the other users.
- *Correctly assign user and system functions.* In the case of a process, some tasks must be performed by users and other by the system itself. Ensuring that functions are correctly identified and allocated is important for usability. The allocation of these functions is done by taking into consideration the human capacities and needs.
- *Iterate on solutions.* User feedback should be considered to iterate the solutions. This iterative process can be achieved by using human-in-the-loop testing, for example. Prototypes of various types can be tested by end-users to implement the new design. These tests will detect and resolve usability issues.
- *Involve multidisciplinary teams.* The development of complex systems involves many skills and objectives. For the design process to be beneficial, experts in the relevant domains must work as a team to ensure that the solution considers all aspects of those domains. This team should therefore involve representatives from the entire system life cycle, from management, business, and engineering, as well as end-users, experts and support staff.

HCD is now used in many domains, of which Human Computer Interaction (HCI) is the leading one. In this field, understanding user needs is essential and HCD is the most widely used approach (Anderson, Norman, and Draper 1988). This orientation explains why we can find most of the fundamental work on human-centered design methodologies in the HCI community.

II.2.1.1 Human-centered methodologies

Among HCD methodologies, sub-domains such as user-centered design, activity-centered design or goal-directed design can be identified (Williams 2009).

- User-centered design is composed of three main phases (Williams 2009) (see Figure II-2). (1) The *design research phase* focuses on assessing users and their needs. This requires a stakeholder-driven planning phase. Once planned, research is conducted with a focus on the system environment in the form of background research, competitor evaluation, users interviews and surveys, questionnaires and other data analysis. The research conducted is then analyzed by the team, which highlights analyses, lists or even clusters of data to be communicated to different audiences. (2) The *design phase* follows the research phase to gather analysis and bring out solutions. These solutions will be modeled, written and prototyped for the next part of the process. (3) The proposed solutions then go through an *evaluation phase*. This phase aim at testing the usability of the solution. This is done through expert reviews, satisfaction questionnaires, formal usability tests, etc.

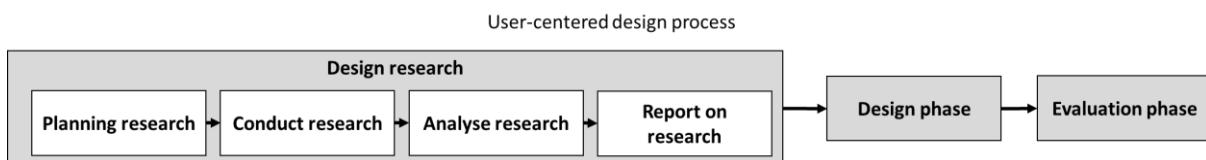


Figure II-2: User-centered design process.

- Activity-centered design is derived from human-centered design because it considers human activity as a central point but does not propose to adapt the tool to the users (Norman 2005). Activity-centered design is the paradigm of adaptation between people and technology. If most HCD methodologies take the side of adapting the tool to the users, the activity-centered design methodologies choose the opposite. Activity-centered design focuses on studying the uses, called activity, of a tool defined by users. Studying these activities allows designers to create tools that allow user to perform their needed activities and to teach them how to use them properly.
- Goal-directed design can be broken down into six steps (Cooper, Reimann, and Cronin 2007) (see Figure II-3). (1) The research step is like the one done in user-centered design with the study of the project scope, interviews with stakeholders and future users regarding their goals, and observations regarding the project environment. (2) The modeling step consists of synthetizing the answers from the research step and modeling these findings. (3) The requirements step will be used to elicit systems requirements from the modeled research findings. These requirements are intended to capture the goals and objectives of the system. (4) The framework step is like the design phase of the HCD method in that the solutions will be define and the "shape and behavior" of the system will emerge.

(5) The refinement step allows to go further in the definition of the solution and refine it to consider as many aspects of the requirements as possible. (6) Finally, in the support step, the goal-oriented design team supports the following actors in the system lifecycle.

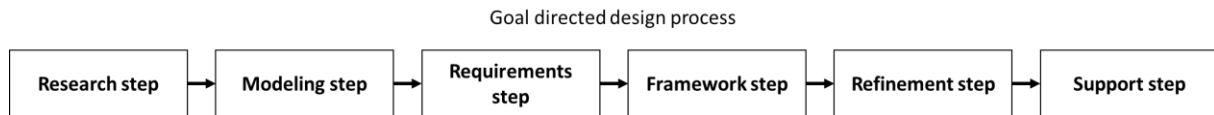


Figure II-3: Goal directed design process.

In examining these design processes, similarities emerge. All methodologies are based on a research/design/creation/evaluation pattern. This pattern aims to:

- Understand the work ahead to orient the system towards the user's needs;
- Define the system model to ensure that it will meet the previously defined needs;
- Create the system according to the defined model;
- Evaluate the created system in light of user experience to refine and ensure the ability of the designed system to meet user needs.

If we examine the activities proposed by these methodologies to achieve the required objective, many are similar:

- Interviews and observation are used to identify user tasks and understand the work to be done with the designed system.
- The modeling of the system before its implementation is also an activity used to allow communication between the actors of the design phase that is used in the presented methodologies.
- During the evaluation phase, the user's capabilities, as observed using the human-in-the-loop simulation, are used to define the potential capabilities of the system to meet the users' needs.

II.2.1.2 Synthesis

The three paradigms presented show two different ways of looking at design for humans. Therefore, while some advocate adapting tools to the user based on theoretical study, others advocate adapting the tool based on the utilization by users of a predefined tool. Activities to be performed during the design process also emerged and were defined to address specific part of the design process. These well-defined methods provide guidelines on how to integrate humans in the design process. The global design community encourages defining the most contextually appropriate design process using parts of previously defined methods to achieve the design goal. Therefore, the defined Reality Anchor Methodology must follow the identified research/ design/creation/evaluation pattern to ensure the implementation of a system that meets the stated objective. Most of the activities identified in these methodologies

can be adapted to answer specific goals and should be found in a situational awareness design methodology, as is the purpose of this study.

II.2.2 Situation awareness centered design

Situation awareness can be used to help users make decisions in a support system (see part 1 section I.2.2). The methodologies presented in this section focus on human situation awareness, as it has been presented as a first step to support human decision making on complex systems. In addition, these methodologies take into consideration the use of remote situation representation tools, such as digital twins, to make the decision.

Ways to improve SA when working with SA Support System (SASS) have been defined (see part 1 Section I.2.3. To ensure the implementation of these principles, methodologies has been defined. Two types of methodologies can be identified: (1) information-based methodologies that focus on the form and content of the interface to provide the correct information to the user and (2) knowledge-based methodologies that focus on the processing of information to display knowledge. These two types of methodology types and associated studies are presented in the following subsections.

II.2.2.1 Information-based design

Information-based design methodologies are introduced in this section. Those aims to design systems that support human situation awareness systems through interface design and information display. This is to be opposed to knowledge-based design methodologies that focus on creating knowledge to support human situation awareness.

Situation awareness oriented

Endsley provided a model of the concept of situational awareness (Endsley 1995) (see part 1 section I.2.2.1). Aiming to improve human situational awareness in the decision-making process, she sought for improving initial model of situational awareness. She made 13 recommendations for situational awareness (Endsley 1988):

- **Information should be regrouped spatially and imbedded into objects** to reduce the number of disparate visual display sources. *In the case of an oil-and-gas site management interface, information related to the liquid levels values of a separator should be attached to a separator component.*
- **Multiple attributes should be linked to each object to support short-term memory.** For example, every information related to a separator should be displayed together on the interface.
- **Objects categorization and pattern recognition** should be made as simple as possible by grouping information. *For example, every same type of valve should use the same categorization to identify them as same types.*

- **Holistic displays** should be encouraged to provide users a top-level picture of the situation. *For example, a general view of the site should be provided on the interface.*
- **Filtering information through overall importance** should help users with information filtering cost. *For example, the pressure inside a separator is overall more important than the internal temperature and should therefore be displayed in this order.*
- Information about **trend or change rate** should help users in the projection level of situation awareness. *For example, the use of separator internal pressure or flowrate trends should be provided to enable the user to see changes more efficiently.*
- **The most important information** should be the **most salient perceptually**. *For example, active detectors reaching value limits should be made more visible than normal condition ones.*
- **Peripheral vision** can be employed for **secondary information**. *For example, main information, like the map should be at the center of the screen where more detailed information can be accessible on the sides of the screen.*
- The use of verbal information should be limited to reduce short term memory use.
- **New information** should be provided simultaneously from **additional inputs** modes like auditory or tactile. However, very important information should have visual redundancy. *For example, new alarms should both use associated sounds and blinking color.*
- Providing **simultaneous access to secondary information on the primary task** as well as allowing rapid reorientation should allow support in case of attentional narrowing. *For example, still providing access to process values when the focus is on a leak detection situation is necessary.*
- **Spatial information** should be provided **into context** for users to relate to its own cognitive map and orientation. *For example, the threshold triggering of a detector should be contextualized on a map.*
- **User workload should be reduced** thanks to **advanced sensors and controls**. Information should be processed internally before being displayed to users to relieve them from the processing load.

Those recommendations were not initially defined as part of a methodology. However, Endsley extended her work emphasizing importance of SA in the design phase by defining an appropriate methodology: the Situation Awareness Oriented Design (SAOD) methodology (Mica R. Endsley, Bolte, and Jones 2003). This methodology, as part of goal-directed methodologies, follows three main steps (see Figure II-4) that are: (1) Performing a goal-oriented analysis, (2) implementing the extracted elements in the SASS and (3) evaluating the users SA to ensure the SA supporting abilities. Once the evaluation is performed, the SASS can be updated based on the results of the SA Global

Assessment Technique (SAGAT). This evaluation technique is explained in part I section I.2.4.1.

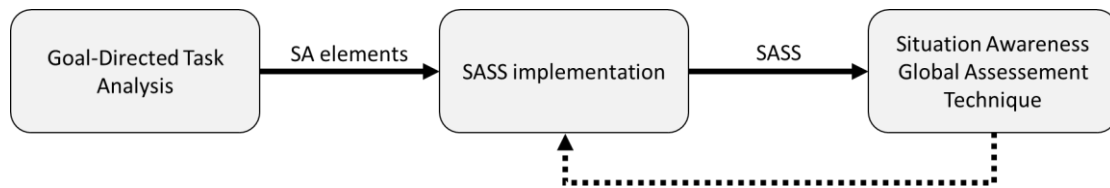


Figure II-4: Situation Awareness Oriented Design model.

This methodology focuses on providing the situational awareness requirements using interfaces. This consideration of SA support focuses on identifying the information needs to be provided to assist users and simply correctly that information in the SASS. Using a goal-oriented analysis (see section II.2.1 on human-centered methodologies) called Goal-Directed Task Analysis (GDTA), the methodology proposes to identify the users' goals and the necessary information about the situation to be provided for decision making (see Figure II-5).

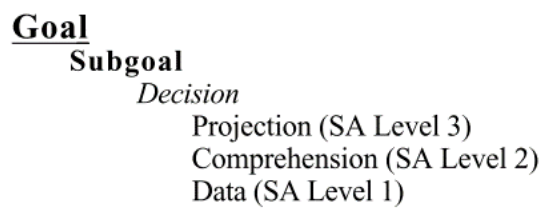


Figure II-5: Format of GDTA. (Endsley 2000)

Example II-1: Example of applied GDTA.

An example of GDTA, applied to the management of an oil-and-gas separation process, is represented in Figure II-6. The goal is to re-start the process on site. A sub goal that can be identified (from many others) is to reach the working pressure in the separator. This goal is based on the decision following the question "is the pressure at or is reaching the wanted value?". This decision will be based on different data and information.

1- Process re-start on site

a. Reach working pressure in the separator

- *Is the pressure at/is reaching the wanted value?*
 - Time until the pressure reaches the set value
 - Amount of pressure deviation to set point
 - Pressure behavior
 - Current pressure
 - Pressure set up point
 - Pressure rate of change

Figure II-6: Example of partial GDTA applied to oil-and-gas process management.

After the definition of the goal-oriented SA requirement, the design principles are implemented. These principles are based on the once introduced in this section and are the following:

- Represent the need for higher-level information rather than low-level data. For example, representing the pressure behavior is better than simply providing the current pressure and pressure set up point.
- Display information according to the objectives. It is better to provide information that is related to the objective rather than unrelated ones. In this example, it is better not to show the temperature as it is not necessary for the purpose.
- Provide an overview of the situation for each objective to facilitate goal change. If only one goal was identified for this example, different goals and sub-goals form the complete decision profile. Moreover, different information will be needed for each. However, providing situational awareness based on the specified information will allow for goal switching.
- Essential cues should be identified and highlighted in the interface to facilitate goal switching. As with the previous recommendation, the important elements of each goal should be displayed more prominently to ensure the user to focus on information associated to different goals and enables goal switching.
- Information that is not related to SA should be deleted.

- The multi-modal display should be used to support parallel processing in a data-rich environment. For example, providing two displays with dedicated goal information will enable parallel processing.

After the design phase, SA is then measured using SAGAT, presented in the SA evaluation section (see part I section I.2.4.1), to ensure the success of the design study.

This methodology proposes multiples concepts for supporting SA in the system design phase like the study of users goals, guidelines for implementation and an evaluation technique. It has been applied in different use cases, such as military command and control system (Mica R Endsley et al. 2003), fire emergency response (Yang, Prasanna, and King 2009), wayfinding system for visually impaired (Alkhanifer and Ludi 2014).

The three-step structure (study, implementation, validation) appears as being a structure that provides the ability for the designed system to support situation awareness. The user study allows to identify the user's goals in terms of situational awareness. Then, these elements can be properly implemented in the tool to provide support to the user's situation awareness. Finally, the evaluation step ensures that the previous theoretical study was complete and that the tool provides the necessary support.

Ecological interface design

Ecological Interface Design (EID) refers to "an interface that has been designed to reflect the constraints of the work environment in a way that is perceptible to the people using it" (Burns and Hajdukiewicz 2017). It focuses on allowing users to perform actions and understand how the action affects the complex system. To support users actions, ecological interface design focuses on supporting the three levels of cognitive control in the Skills, Rules, Knowledge (SRK) model (Vicente and Rasmussen 1992).

If EID does not directly focus on SA, this design paradigm has shown an ability to support it for process control in unanticipated events, and while it is not a direct player in improving SA in every situation, it could be incorporated into other human-centered design methodologies (Burns et al. 2007).

To understand further the EID paradigm, it is necessary to understand the SRK model. SRK, as defined by Rasmussen (Rasmussen 1983), proposes a decomposition of human behavior when performing an action into three types of cognitive behavior that must be supported as defined by the EID principles (see Figure II-7):

- *Skill-based behavior* (SBB) is manifested by automated sensory-motor responses without conscious control.

The principle associated with EID is that "to promote interaction through spatio-temporal cues, the operator must be able to act directly on the display, and the

structure of the displayed information must be isomorphic to the part-whole structure of movement" (Vicente and Rasmussen 1992).

Following this principle, the interface control should follow a pattern to improve SBB. A mapping of controls should be done in the interface to allow users to perceive the patterns and improve the execution of the patterns.

- *Rule-based behavior* (RBB) begins with the recognition of unconsciously perceived signs at the level of skills. The recognized state will be associated with a task to be performed. The task will be performed following learned rules.

The principle associated with EID is to "provide a consistent correspondence between the constraints of the work domain and the cues or signs provided by the interface" (Vicente and Rasmussen 1992).

Following this principle, the cues provided by the interface must be consistent with the work domain to ensure correct recognition of the system state. Selecting the correct display of cues for state recognition is therefore a solution encouraged.

- *Knowledge-based behavior* (KBB) is the highest-level behavior and will start with the identification of symbols that will lead to a goal-driven decision for tasks to be performed. The tasks will be planned and executed following the learned rules. The decision-making models presented in the part 1 section 1.2.1 are examples of knowledge-based behavior.

The principle associated with EID is "to represent the domain of work as a hierarchy of abstraction to serve as an externalized mental model that will support knowledge-based problem solving" (Vicente and Rasmussen 1992).

An abstraction hierarchy follows five properties (Mesarovic, Macko, and Takahara 1970):

- o Each level provides a different description of the same system;
- o Each level has its own set of terms, concepts, and principles;
- o Each level is selected by the user to provide a particular view of the system based on their knowledge and interest;
- o System operating constraints affect the levels from the bottom to the top;
- o The understanding of the system in relation to its purpose increases as the user progresses through the levels.

Implementing this type of hierarchy would allow the user to have a better knowledge-based understanding of the system through the multi-models of the hierarchy.

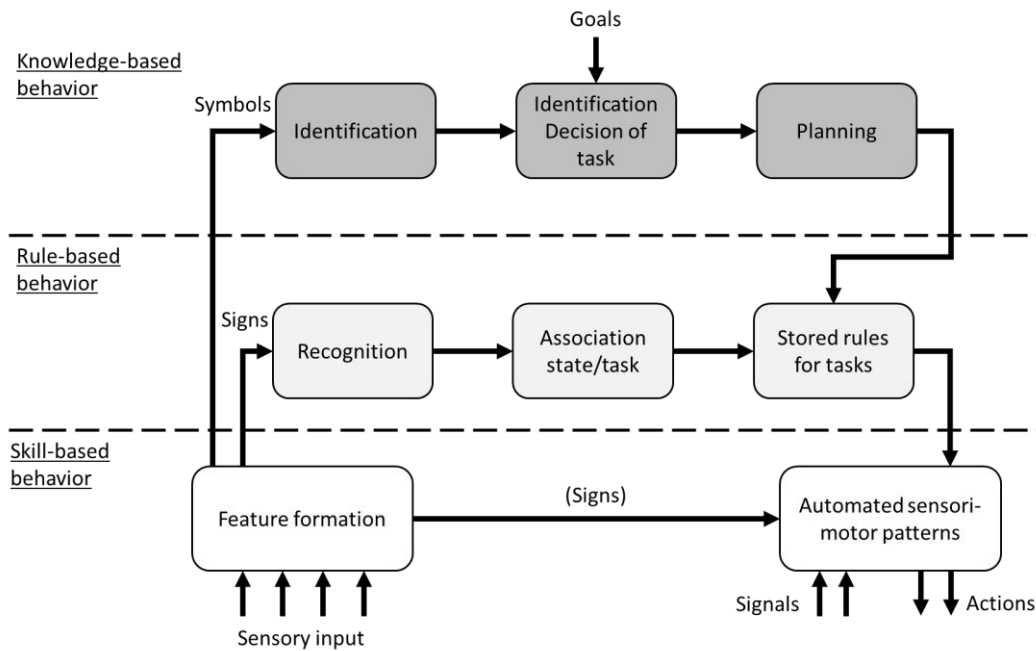


Figure II-7: Simplified illustration of three levels of performance of skilled operators. (Rasmussen 1983)

Example II-2: Example of application of the Skill, rule, knowledge principle.

Application of these principles in the case of the control room interface of an offshore oil and gas platform:

The SBB improvement could be achieved by applying the same scheme for closing or opening control valves (Select valve -> select open to open or Select valve -> select close to close). In this way, the user can perform the action at their skill level, without conscious control.

RBB improvement could be achieved by identifying the correct cues that describe the state of the systems, such as the internal pressure of a separator and a trend in that pressure that would allow the user to recognize an unusual pressure decrease that might indicate a leak in the process.

Enhancement of KBB could be achieved by displaying different types of models of the system, such as a process model and a geographic model of the oil-and-gas platform. This would allow the user to understand the system from both aspects.

The EID method is composed of five steps (see Figure II-8):

- The definition and organization of the target: System boundaries are defined and the design team is composed with the goal of bringing together human factors specialists and domains experts.

- The work domain analysis: A functional goal is defined as the center of an abstraction hierarchy. The elements of this hierarchy are defined and the relationship between each element is made explicit (Howie et al. 2000).
- The transformation of information into variables: The identified elements of the hierarchy are redefined as variables. Those variables are then studied in terms of the relationships between them and their availability.
- Information visualization: Display modes for selected variables are defined to allow for user to consult the information and to support the RBB.
- Design review and evaluation: Finally, the designed interface is evaluated in terms of visualization effect using heuristic techniques for semantic mapping (Hansen 1995).

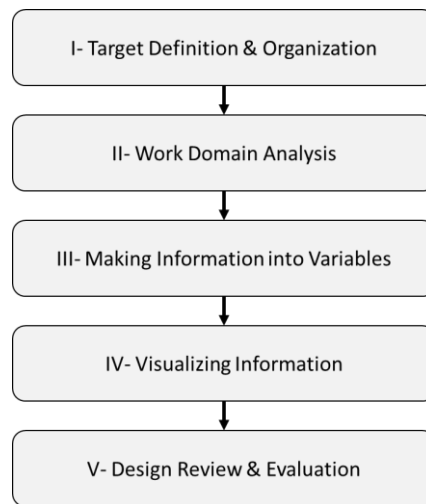


Figure II-8: Process for EID based on (Kim et al. 2012).

Similar to situation awareness-oriented design principles, ecological interface design focuses on improving the user's perception of the system but this time with the goal of supporting the execution of their actions. A methodology based on a similar philosophy of domain investigation, tool implementation, and effects examination is proposed and encourages the use of similar steps to ensure the implementation of a SASS.

In addition, the principles of EID make it clear that the system model is necessary for the user to understand the state of the system and select the correct action. This is similar to the process of situation awareness for decision making and the need for the decision maker to know the system and its situation. Concepts such as using an abstraction hierarchy to represent different models of the goal-oriented system could be used to ensure the user has complete awareness of the system in a SASS.

II.2.2.2 Knowledge based design

While the previous two design principles focused on obtaining the information users need to acquire full SA and displaying that information, the next principle focuses on human knowledge and how it is used by users.

Distributed Situation Awareness methodology

The human factors perspective on the concept of situation awareness (see part 1 section I.2.2.3) is expressed in the Distributed Situation Awareness (DSA) paradigm (Stanton et al. 2006). According to this paradigm, situation awareness is a component of both humans and systems. The interactions between humans and systems are the reasons that allow each other to have full situation awareness. Designing a system to enable full situation awareness involves studying distributed situation awareness to ensure its integrity for decision support. This is where the DSA methodology comes in handy.

The DSA methodology is composed of three parts (Stanton et al. 2006) (see Figure II-9): (1) the elicitation of the knowledge held by each party, (2) the extraction of “knowledge objects” and (3) the representation of the relations between the “knowledge objects” and their activation.

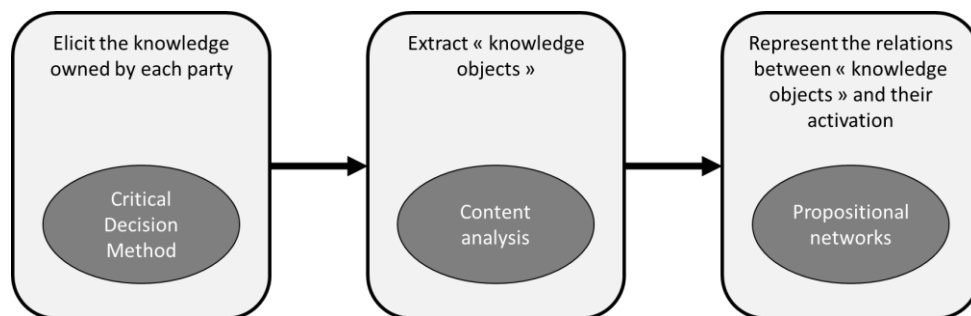


Figure II-9: Distributed situation awareness methodology (Stanton et al. 2006)

The elicitation of the knowledge held by each party is conducted using the Critical Decision Method (CDM). This method consists of asking the interviewee to recall incidents and analyze them in light of defined questions (Klein 1989). This analysis is structured in four steps which are:

- *The briefing and initial recall*, where the interviewee is given context and general questions are asked to initiate an initial recall of incidents.
- *Identification of decision points*, where the interviewee is asked to identify the moments in the situation where he or she had to decide.
- *The decision point survey*, where the designer asks specifically defined questions to the interviewee based on the method developed by O'Hare et al (O'Hare et al. 1998).
- *Verification*, where the interviewee is asked about the relevance of their previous answers.

This part is used to generate results tables containing the responses to the probes.

The extraction of “knowledge objects” is performed by content analysis. Knowledge objects are defined as “entities in the world that people detect, classify and manipulate”, such as weather for example. These objects are identified by reducing the results to important words in the responses such as “weather”, “gas”, “pressure” or “humans” for example. More than just objects, knowledge objects can be organized into an object network. This network focuses on the mapping the concepts identified in the interview results.

The representation of the relationship between the “knowledge objects” and their activation goes further and applies the Propositional Network (PN) paradigm. Propositional Networks are networks composed of nodes, where words respond to basic statements such as “... the representation of the environment surrounding the system”, and links between nodes that are labelled to define the relationship between nodes such as “has” or “needs” for example. The use of such a network allows to represent the knowledge used by the decision maker during its tasks. It allows to identify the knowledge held by different entities of the DSA and to map the knowledge acquisition for the SA. The salient knowledge objects identified in this method should be given specific attention in the design of a SASS to ensure situation awareness by users.

This methodology demonstrates the use of a step-by-step analysis of user tasks and the elicitation of key knowledge objects needed by users to acquire SA. It uses guided interviews, activities recommended for user-centered design, as a tool for eliciting user knowledge.

Once knowledge is obtained, the implementation of knowledge models provides an understanding of what the user needs to perform the required tasks. Knowledge maps are used to represent the humans needs and to identify points of interest for future design activities.

However, this technique does not highlight the levels supported by the knowledge objects and does not provide guidelines for the implementing the extracted results in a SASS.

Knowledge representation for Intelligent SA system methodology

Intelligent SA systems (ISAS) are part of SA support systems. The intelligence of the system represents its ability to react to different situations (Butakova et al. 2019). Butakova et al. defined a method to design the knowledge representation for ISAS (see Figure II-10). This method follows the following eight steps:

- The first step is to acquire information about the situation and the work to be done. The necessary information can be obtained from various databases, sensors or exchange protocols. The objective is to build a data warehouse.
- The second step focuses on the formalization of the acquired information. The formalization is structured in ontologies where concepts are linked together.
- The third step focuses on generating a collective ontology based on experts' ontologies. To generalize knowledge from different sources, a collective ontology formed from the concepts of the previously defined ontologies is created.
- The fourth and fifth steps aim at identifying the critical situation-related elements in the previously defined ontology. This elicitation is performed using the Rough-Set-Based approach (Chernov et al. 2017). Rough Set Theory (RST) is a mathematical theory that focuses on classifying data using boundaries. Data that fall between the set boundaries are part of a specific class and data beyond are part of other classes. Bayesian probabilistic methods are used to overcome possible errors and assumptions. This step ends with the identification and classification of a specific set of items based on the situation.
- The sixth step is to implement the reasoning logic. This logic focuses on describing how ISAS should respond to specific identified situations.
- The seventh step is to measure the user's situational awareness using the selected method (see section 2.2.4). This measurement will ensure that the defined elements of the ISAS provide the user with situational awareness.
- The eighth step focuses on improving the user's emotional response to the situation. This step aims to improve the user's affective behavior according to the affective computing approach (Vlachostergiou, Caridakis, and Kollias 2014).

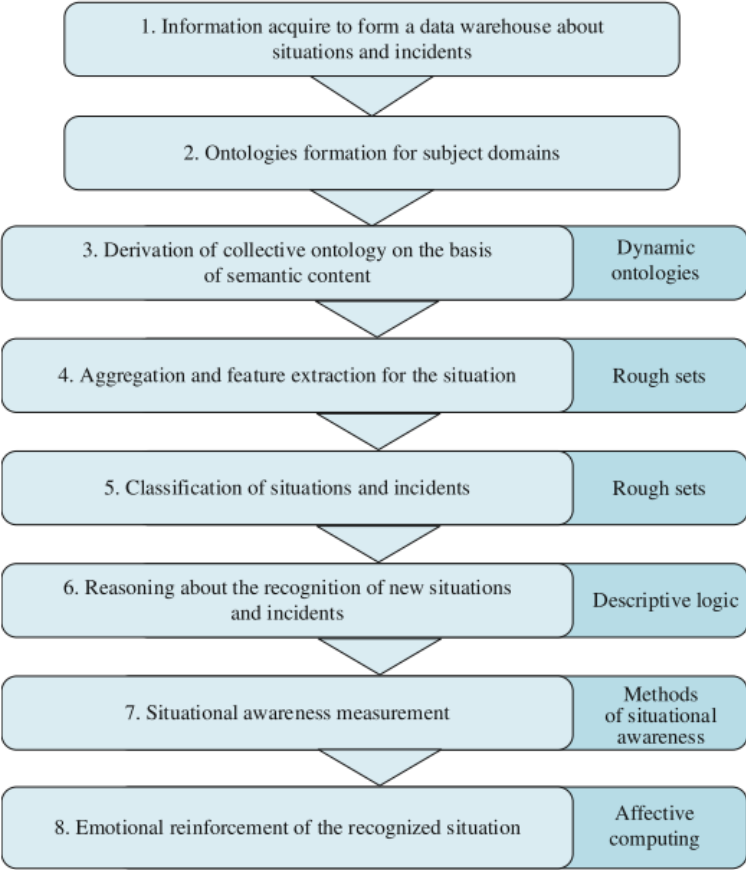


Figure II-10: Knowledge representation for ISAS methodology (Butakova et al. 2019).

Example II-3: Example of ISAS methodology application.

The application of the ISAS methodology to the case of the design of the control room tool of an oil-and-gas site relies on the following examples:

- First, information can be acquired from the REX (Return of Experience) data base where incident reports are stored for analysis and analyzed. The company’s rules and regulations also reflect the knowledge gained about operations and incident management. These two sources could be used to form an incident management data warehouse.
- Second, the information can be structured in the form of an ontology. Concepts around gas leakage can be formalized as “a gas leakage generates a gas cloud” or “gas cloud has a gas nature” (the nature can be CO₂, CH₄, H₂S, or other).
- Third, a generalized ontology that aggregates/regroups the previously generated knowledge is formed. This ontology would aggregate concepts from different experts, such as knowledge related to equipment maintenance, gas leakage management or process control.
- Fourth, the elements defined as part of the situation described in the ontology are extracted. Elements such as work permits, the number of people in the vicinity, or the location of a gas leak can be identified as features of a situation.

- Fifth, situations can be classified. This can help identify the differences between gas leak situations with personnel nearby or not, for example.
- Sixth, based on the defined situations, the information can be used by ISAS to adapt to the situation. For example, in the case of a gas leak situation with a work permit nearby, ISAS can display work permit.
- Seventh, the ISAS is evaluated on its ability to support the user's situation awareness. This evaluation can be done by different methods, such as the SA rating technique for example. This method is a subjective personal assessment of the user that shows how well the user considers to have a good SA in terms of specific identified factors (see section 2.2.4).
- Eighth, the user's emotional response to situations is studied to identify ways to improve the design of the ISAS. Following this approach, situations identified as unstable would benefit from a higher state of arousal on the part of the user, for example, as this should ensure the user's ability to respond to events that arise.

This methodology shows the use of different tools to, once again, generate an understanding of the user's work situation that will then be studied. The study of the situation is carried out through the representation of knowledge using ontologies and allows to define and classify situations by their critical elements. Within the framework of ISAS abilities, the intelligent logic of reaction to the situation is defined before evaluating the effects of ISAS on the user. This evaluation is performed from both the SA and emotional perspectives. This latter point of view allows for further improvement of ISAS once its ability to provide SA to the user is validated.

While the steps and logic of the methodology are well defined, the content of some of the steps needs to be further detailed to ensure their implementation. This methodology considers improving the overall effect of the system on the user after ensuring its ability to support SA. This step brings new perspectives to the user-centered approach because it does not focus solely on the ability to support SA but seeks to improve the tool for the user.

II.2.2.3 Synthesis

In reviewing the design principles and methodologies, several steps can be identified that are necessary for a methodology focused on supporting SA.

First, a user study must be conducted to identify the work situations and user needs. This step can be done using the knowledge base study and user interviews. The analysis of the extracted information allows to perform a goal-oriented analysis and to identify the elements of a situation necessary for the user to acquire the SA.

Second, the implementation of the SASS can be carried out, considering the elements defined above. During this implementation, the SASS must make all critical information available. This step is performed in two dimensions, (1) ensuring the availability of information and (2) by implementing the information in the interface.

Third, the SA must be evaluated to ensure the capabilities of the SASS. This evaluation, like the goal-directed analysis, can be performed using different possible techniques like SAGAT or SART for example (see part 1 section 1.2.4). Each technique will assess different aspects of the user's SA, from their ability to perceive specific items to their subjective assessment of their available mental abilities.

Finally, the interface can be improved because of further study of user behavior using the designed SASS. Focusing on the interface will improve how the necessary information is made available to the user and optimize its acquisition by the user. This can be done through activity study or following the affective computing approach for example.

None of the methodologies presented in this section has a comprehensive approach of all these steps. This study therefore proposes to define such a methodology and to study its implementation.

II.3 Reality Anchor Based Methodology

There are various recommendations and methodologies for designing a SASS (see section 1.2). It has been identified that:

- A SASS design methodology must study the user to identify their SA needs. This allows the designer to understand the user's needs in terms of their purpose and/or tasks.
- The results of this study should then be implemented into a SASS. The implementation of the study results into the SASS is intended to create a SASS considering user needs in terms of SA.
- Once the SASS implemented, it must be evaluated on its ability to provide SA to its user. This evaluation will ensure the successful implementation of the user's needs extracted from the first study.
- Once the basic ability of the system to support SA has been validated, the uses of the SASS need to be explored to improve the usability of the system and further support user acquisition of SA.

However, while they use interesting concepts to ensure the ability of a SASS to support user SA, none of them seems to propose a complete design cycle following the principles of user-centered design.

Therefore, this study defined the Reality Anchor Based methodology with the aim of proposing a human-centered methodology focused on the design of user SA tools.

II.3.1 Introduction to the methodology

This methodology (see Figure II-11) proposes to elicit necessary situational elements that should be available in a decision support system and implement them in the SASS to ensure decision-maker's situation awareness. Furthermore, this methodology does not only focus on the design of a tool but also proposes to validate the results through user testing and support the user SA through an activity study.

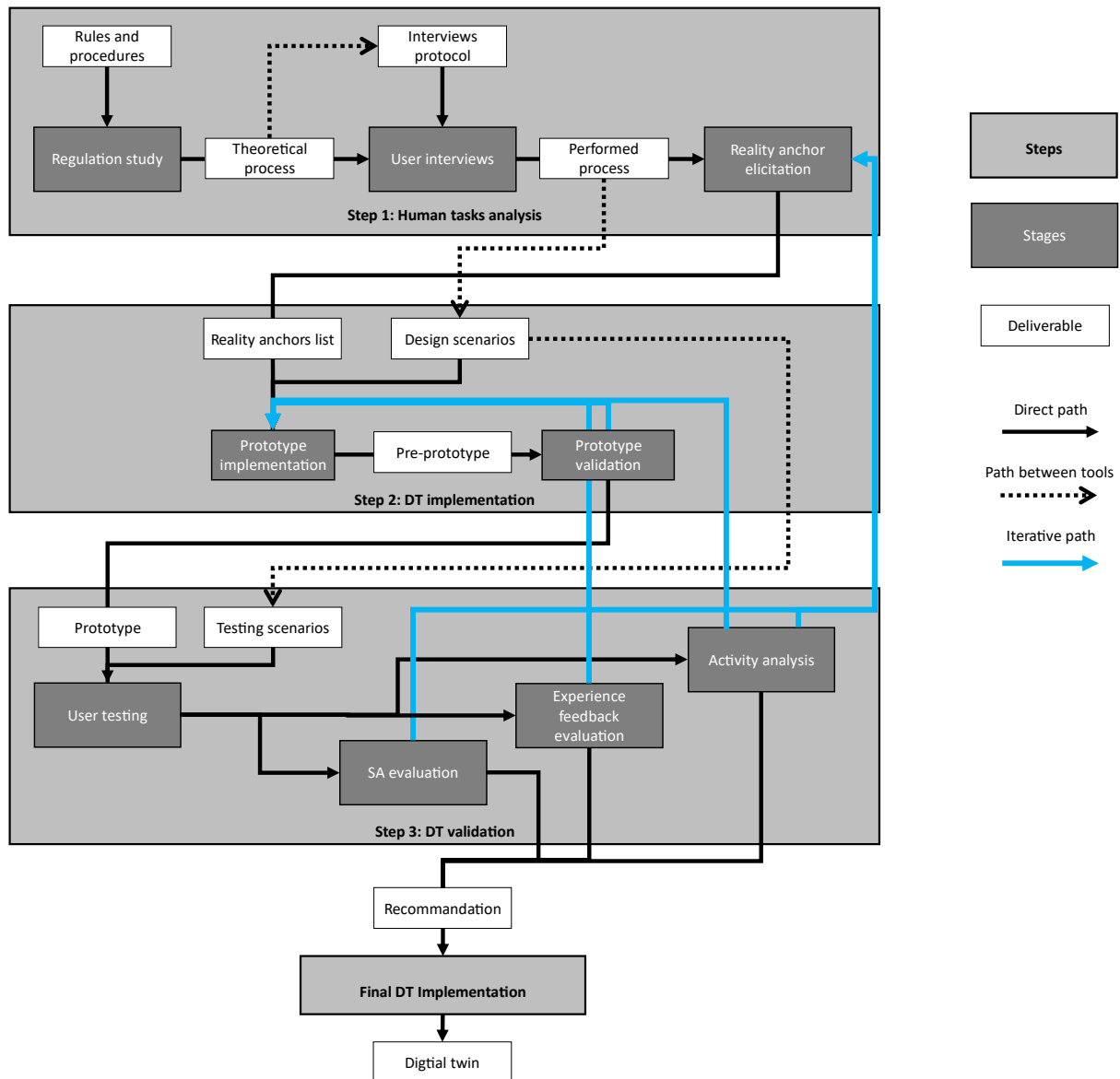


Figure II-11: Reality Anchor Based methodology process representation.

It 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 will enable to analyze activities performed and the reality anchors used/missing. This analysis will allow iterating on

the anchor elicitation if necessary to ensure the best human situation awareness (iteration loop represented in blue).

At the end of this process, the SASS can be implemented to provide situation awareness to users.

This methodology can be used to design new SASSs that have not had previous iterations or to improve an existing SASS.

II.3.2 Step 1: Human task analysis

Human task analysis focuses on understanding user needs in terms of situation awareness to provide the elements necessary to perceive, comprehend, and project reality in the SASS. This analysis is broken down into three steps:

- The formalization of the theoretical process focuses on the analysis of the company's regulations to extract a recommended decision process. This step provides the designer with knowledge about the tasks to be performed and identifies recommended sources of information. This regulatory review step is described in section II.3.2.1.
- Since the differences between the tasks of the recommended decision process and the user experience-based decision process are known (Hollnagel 2015), interviews with current or future decision makers will result in a decision process that is closer to the operational reality. These interviews can focus on the decision process thanks to the knowledge acquired on the recommended theoretical process. This interview stage is described in section II.3.2.2.

The real process extracted from the interviews is then analyzed according to a Cognitive Function Analysis (CFA). Cognitive functions (Boy 1998) are defined from the identified tasks of this decision process in a specific context and the resources related to the real-life realization of these tasks allow to define reality anchors (section II.3.2.3).

II.3.2.1 Stage 1: Regulations study

Companies usually implement rules and procedures to standardize 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 of the company.

The regulation review step focuses on finding the regulatory documents related to the decision-making situations that SASS will support. Once the documents have been identified, the study of these documents will reveal the tasks to be performed, the tools to be used and possibly complete processes to be followed. This knowledge will allow the implementation of a first task diagram. The Business Process Modeling Notation (BPMN) (White 2004) is the one we have chosen for this representation because it allows the representation of multi-actors processes and decision nodes.

The BPMN specifications allow for the representation of events, activities, and gateways and thus the formal modeling of most processes. These elements are linked using three types of representations of sequence flows, messages, and associations to connect tasks in a continuous process. Since processes may involve the participation of multiples actors, human or system, navigation corridors can be implemented to identify actors and their related activities. Further details can be added by representing data objects, groups, and annotations. The use of all these graphical objects ensures a sequential representation of a decision process and allows for the representation of complete processes in a simple, comprehensive and formal way that can be broken down into more specific elements if necessary.

Example II-4: Example of Regulation study.

If we take the example of a low-threshold alarm management process in the control room, the following process could be expressed as a rule: "First, when the alarm is triggered, in the control room, operator checks the alarm information on the SASS. To get further information, the validity of the detected anomaly is questioned, the control room operator may inform the field operator of the problem and ask him to go to check at the location of the alarm. While the field operator goes to the scene, the control room operator continues to monitor the process and any additional alarms that may occur. Once on site, the field operator completes his/her investigation and informs the control room operator of his/her conclusion. The control room operator then will start to take final action to resolve the problem.". This process can then be displayed using the BPMN format, as shown in Figure II-12. This figure shows three actors which are the SASS, the control room operator, and the field operator. The process starts with the activation of the alarm and ends with the confirmation of the identified anomaly. Multiples tasks are performed by separate actors and information is used.

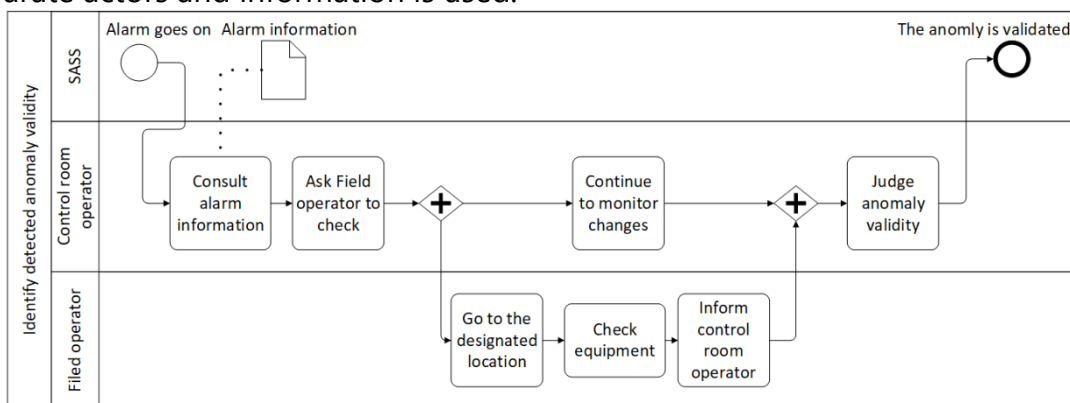


Figure II-12: Example of BPMN representation.

This stage will give the designer general knowledge about the tasks to be performed by the users and will help to formalize the interviews to be performed later.

II.3.2.2 Stage 2: Interviews

The study of regulations can help formalize a complete task model for the decision-making process (specifically in the case of predefined process). However, human tend to apply processes that are close but nevertheless different (Hollnagel 2015). This difference between the recommended process and the executed process lies on multiple factors including the familiarity with the situation, the time constraints or the decision maker decision awareness and his/her ability to adapt his decision-making process according to this awareness (Stanners and French 2005). Therefore, the executed process must be identified to adapt the SASS as best as possible to the human's needs. Not considering the performed process can lead to errors or unexpected risks due to the emergence of unforeseen behavior.

To identify this process, interviews with domain experts could be conducted. Different types of interviews can be conducted and are described in the User eXperience (UX) design literature (Lallemand and Gronier 2018; Unger and Chandler 2009). Three types of interviews can be founded in literature:

- Guided *interviews* consist of a series of questions that the user must answer. It is a very rigid interview model that guarantees answers to specific questions. However, this model assumes a specific question and a very good understanding of the domain. Questions that might be asked in such an interview might be "How many times a day do you use SASS? In performing this specific task, what information do you use?".
- Semi-structured *interviews* are composed of open-ended questions. The main categories of interests in the field should be identified, but the use of open questions will allow the user the freedom to refine his or her response with his or her knowledge of the field. Other "off-the-cuff" questions can follow his or her answer to guide the rest of the interview based on the knowledge just gained. This interview model assumes moderate domain knowledge to identify question categories. This model is less rigid and allows for exploration of the domain while maintaining specific response objectives. Questions that might be asked in this type of interview could be "Regarding collaboration with other staff: what are your interactions with your colleagues? You said you interact with this specific worker, can you elaborate on your interactions with this worker?".
- Unstructured *interviews* are composed of fully opened general questions. This interview model focuses on exploring a domain and can be conducted without prior knowledge of the domain. A main starting question is identified and other "improvised" questions are asked to drive the interview as it progresses. This model is entirely flexible but assumes an ability to capitalize on unstructured knowledge and might miss areas of interest. Questions that might be asked in such an interview could be "What does your work is about? What tools are you using?".

In the case of this methodology, the objective is to extract the user's decision process. As knowledge of the process has already been extracted from the last stage (see section 2.2.1), undirected interviews are not necessary and would be more time consuming. However, directed interviews would reduce the user's ability to express his or her own process and may constrain the user to the regulated process. Moreover, direct interviews must be performed by domain experts which is not always the designer profile. Therefore, to keep the interview on a specific track but give the user the freedom to express their variation from the regulated process, it is advisable to use semi-structured interviews to capitalize on the knowledge gained from studying the regulation. To identify the tasks performed during the decision process we propose to focus on the following categories:

- **Tasks performed.** To identify the task performed by the user in their decision-making process, the questions used to open this category can be "Could you talk to me about the last time you faced this situation?". Such question is intended to get the user to refer to a situation and provide details about how they resolved it.
- **Tools used.** From the tasks identified in the previous theme, it is useful to know what tools can be used to acquire information and make decisions. A question that could be used in this category might be "What media do you use in this situation?". This question should lead the user to talk about the tools and can trigger more detailed questions about the tools and their use.
- **Accessible information.** Specify the information used for decision making, including information that is not part of the usual tools. Based on the tools previously identified, a question used could be "What do the tools give you access to?". This question does not use the term "information" to ensure that the user does not focus solely on what he or she labels as "information." The user should describe the information or knowledge they use about the tools.
- **Interaction with people.** Focus on the interaction between the user and other workers. These individuals may have more knowledge about the tasks at hand and may also be considered future SASS users. A question to begin this category could be "Who do you interact with in this type of situation?". This question should lead the user to define its interactions if they have not been previously discussed.
- **Acquired knowledge.** Focus on how the user acquired their knowledge. This may reveal other sources of knowledge for the designer to better understand the user's work. This category can be addressed by asking "How did you learn to respond to such situations?". The answers to this question should identify the sources of knowledge used by the user.

These interviews should be performed with experts of the field but can be expanded to include other stakeholders involved in the decision-making process. Broadening the

panel of interviewees allows for a broader view of the decision-making process, its variations and the information or knowledge needed to carry it out.

At the end of these interviews, the designer should have formalized a real decision process with BPMN. This process should be based on an initial list of identified tools and information sources related to the decision process. The identified tasks will be studied in the next step.

II.3.2.3 Stage 3: Reality anchor elicitation

Tasks carried out by the users are identified and certain information necessary for the realization of this process is identified thanks to the interviews. However, to go further on the analysis and obtain information related to the perception of reality, a cognitive function analysis must be carried out (Boy 1998).

A cognitive function is defined as the transformation from a task, that is prescribed, to an activity, that is effectively done (Boy 1998). This cognitive function is defined as being composed of different variables (see Figure II-13):

- The role of the function is related to the purpose of the function. An example can be "Read a thesis manuscript".
- The context of the function refers to the specific condition in which the function is executed. An example might be "Read on my computer, at work".
- The physical resources that are physical elements used by the human to perform the function. An example can be "a computer screen or a document".
- The cognitive resources refer to the cognitive elements, which can be cognitive function themselves, necessary to perform the function. An example can be "the understanding of the language used or the eyes of the readers".

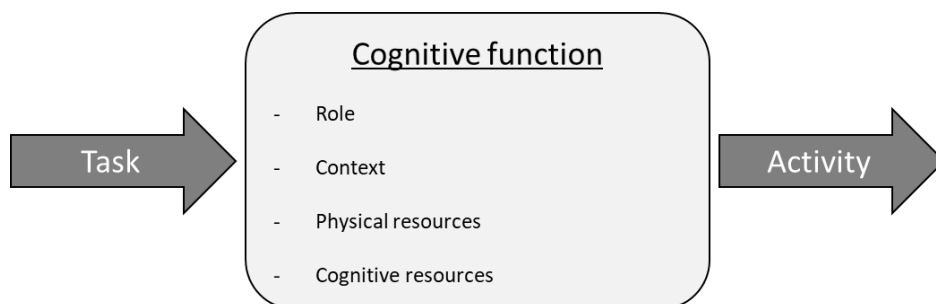


Figure II-13: Cognitive function definition. (Boy 1998)

It is defined in the HCD literature that function allocation to the agent is an important step in the implementation (Pacaux-Lemoine et al. 2022). However, this methodology only focuses on reality perception and the function studied in this step are not being reallocated. In this case of reality perception through a SASS, we have defined the concept of reality anchor. A reality anchor is defined as useful *elements of the situation necessary for humans to enable them to grasp reality and acquire a meaningful*

situational awareness that supports the decision-making process (see section II.1). These reality anchors are, by definition, essential elements to be implemented in a SASS situation model to ensure users' ability to gain situational awareness and make decision. Therefore, this step focuses on identifying them for further implementation. Reality anchors are defined by focusing on each task to identify the cognitive function needed to perform it.

Example II-5: Example of cognitive function analysis.

If we take the example of the decision process for "gas leak management" (see Figure II-14), one of the tasks to be performed would be "check the validity of the detected anomaly". This task can be performed using the cognitive function "Acquiring information".

The resources of this cognitive function can be identified as "the alarm signal", "the description of the alarm" for the physical resources and the cognitive function "linking the alarm to a process step" within the cognitive resources.

The cognitive function used as resource can itself be identified as using resources. As part of these resources, the "process representation" is related to the real world and is therefore a reality anchor.

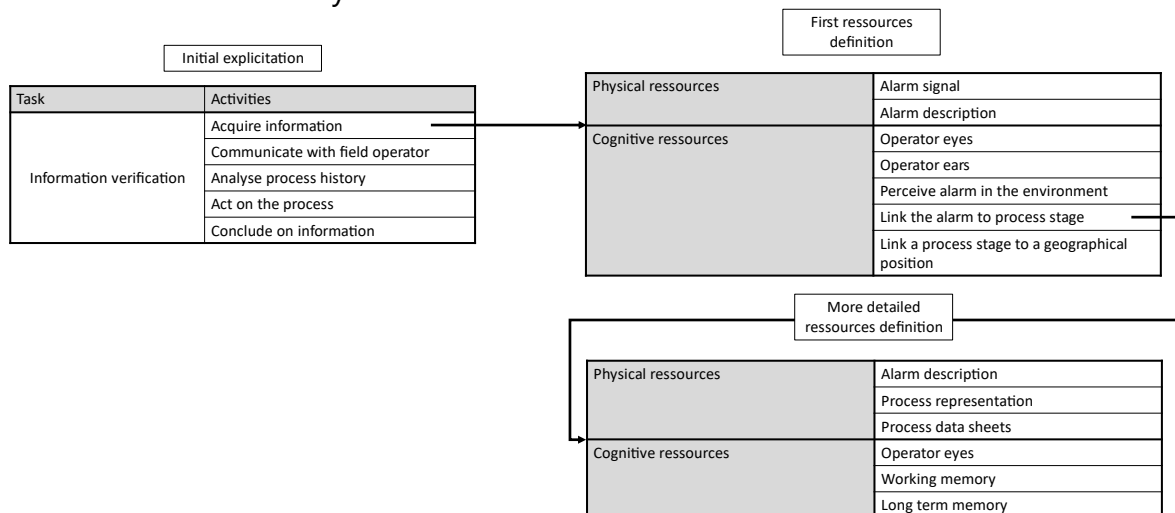


Figure II-14: Example of CFA analysis.

In the case of the implementation of such SASS, having this information is a necessity to enable the execution of the function.

In this first step, the designer has gained knowledge about the user's decision-making process. By first using company regulations and knowledge data base, he or she can create an expected decision process. This process and the acquired domain knowledge are used to conduct interviews that aim at identifying the tasks and tools used by the user to achieve the decision-making goal. With greater precision, the reality anchors used in the process are elicited to ensure

that they are present in the SASS. Making these elements of the situation accessible to the user should enable SA through the SASS. The next step will be to implement a prototype and conduct testing to evaluate the ability of the SASS to support SA.

II.3.3 Step 2: SASS implementation

This step focuses on the implementation of a SASS prototype that contains the previously identified reality anchors. This implementation is done using a human-centered design paradigm. This paradigm is used to ensure that the SASS addresses both usability and display of the critical SA elements identified as reality anchors in the previous step. This implementation involves two steps:

- The prototype implementation stage focuses on the implementation of a prototype that allows access to the reality anchors defined earlier. To perform realistic tests with users, the implementation of the scenarios, resulting from the interviews, in the prototype is also performed in this step.
- The implemented prototype will then be iterated with user feedbacks to improve the usability of the interface.

II.3.3.1 Stage 1: Prototype design

To validate the obtained reality anchors, human involvement is necessary. However, the implementation of a full SASS could have an excessive cost in terms of time and money due to the complexity of the system to be supported by the SASS. Therefore, the use of a well-defined prototype is recommended. The prototype developed here must focus on making the reality anchors live through the interface.

The prototype should represent one or more realistic scenarios based on user experiences gained from the interviews. The implementation of such scenarios will allow testers to relate to known situations. Furthermore, the use of scenarios as a basis for interface implementation has its origins in Carroll's theory of "Scenario-Based Design" (Carroll 1997). As defended by Carroll, scenarios address five technical challenges (Carroll 1999):

- Scenarios bring reflection on the content of the work.
- Scenarios are both concrete as impregnated with reality and flexible as elements of the reality can be altered to create variations.
- Scenarios can bring different views of a same interaction, helping to consider consequences of the practices.
- Scenarios can be abstracted and categorized to generalize and address technical challenges thanks to the extracted technical knowledge.
- Scenarios promote work-oriented communication with stakeholders and enable to bring in expert knowledge more easily.

According to the principle of Scenario-Based Design, the prototype can be implemented with a focus on assessing the situation awareness evaluation of users. These scenarios can be defined in two different dimensions.

- The first dimension to study is the situation in which the scenario takes place. This dimension represents the context that will be used to study the user's situation awareness. The situation must be defined by ensuring that all extracted reality anchors are defined in the scenario situation. The defined situation can be dynamic or not. In the case of a dynamic situation, the state of the situation must be defined as well regarding its chronological evolution.
- The second dimension to be studied is the use of the tool by the user. Once the situation is defined, it is possible to predict the action to be performed by the user on the tool. The prediction of the uses of the tool allows to design the interface by considering its probable use and, thus, to provide indications on the way the tool must work and ensure its usability.

Defining those two dimensions enables to define a complete scenario on which to design the SASS upon.

Example II-6: Example of scenario definition.

Considering the case of gas leak management by control room operators, a scenario defined according to the rules presented above could be described as follow.

In this situation, a gas leak emerges on the process making the pressure drop on a monitored compressor. Two minutes later, the gas detection alarm goes on. The weather is cloudy and the wind is blowing from the east at 10 knots No operator is near the leak.

For applications, the operator looks at the alarm details and immediately call the field operator using its radio. He asks him to go to the compressor location. Once there, the field operator calls the control room operator back and tells him that he hears a whistling sound coming from the entry of the compressor and that he is the only one present. The control room operator looks at the process value of the compressor and requests immediate action as the anomaly presence is validated even though the limits for the automatic isolation process have not been reached yet.

As an example, the definition of such scenario presents the elements of the situation that must be perceive by the control room operator to validate his SA. As for his use of the tool, this scenario indicates for example that the alarm information must be directly available because it is his first action. Radio access must be available as well along with a complete view of the process.

As for the implementation of the prototype, the design should try to remain as flexible as possible to facilitate iterations and adaptation to the user. This flexibility will become essential in the next step.

II.3.3.2 Stage 2: Prototype validation

Once the prototype is implemented, its validation by experts is necessary, as recommended by User eXperience (UX) design methodologies (Lallemand 2015; Unger and Chandler 2009). The expert considered at this stage refers to the user who has experience using similar tools and executing the process defined in the interviews. The validation of the prototype can take the form of a prototype review with an expert.

This review can take different forms. The prototype can be presented to the user through a demonstration by the designer. This technique allows for a quick presentation and ensures that all aspects of the prototype are presented. However, this method does not guarantee the involvement of the expert in the process. To ensure his involvement, it is preferable to prepare textual design scenarios based on the scenario used for the design. During the implementation phase, many scenarios can be defined to ensure to catch every aspect of the work are captured. Some of these scenarios will be selected to be used for testing. The selection of the scenarios is to ensure that the user should have access to all aspects of the prototype. The scenario used may be the same as those used for evaluating the SA evaluation later in this methodology.

When presenting the prototype to the expert, ask him/her to focus on two points:

- The interface: must be realistic enough and comply with domain codes, such as the meaning of colors or equipment symbols. During the review, the expert is asked to focus on functionality. The expert's comments may be "The color red should be used for alarms" or "The size of the writing is too small to be easily readable."
- The scenarios: selected scenarios must be realistic enough to involve the users in to be engaged by the proposed situation. If the choice of scenarios is left to the designer according to the effect he wants to create on the user, their validity must be evaluated by the expert. This ensures that the scenarios are related to the tasks to be evaluated and that the form of the situation corresponds to realistic situations. The comments of the review could be "The situation evolves too slowly, in this case the situation would degrade more quickly" or "in this case, the value of this part of the process would evolve in this way".

Based on the feedback from the expert, the prototype is improved to ensure the validity of the next evaluation. As far as the interface is concerned, the modification can take the form of color changes, changes in the accessibility of the information, changes in

the shape of the icons or an adaptation of the information format. The objective is to obtain an interface that is familiar to the user to increase the realism of the prototype. For the scenarios, some elements may be considered impossible to achieve at the same time or some values may seem unrealistic. Changing these scenario elements to more realistic events will help to provide better user involvement in future SA evaluation tests.

This iterative process should be done with different experts to ensure best results. The protocol used to assess situation awareness can be tested at the same time using the same scenarios. This will ensure a good basis for subsequent testing and evaluation.

In this second step, the designer implemented a prototype that can display all the necessary information for SA. This implementation was done based on defined scenarios that connect the prototype to user work situations and create a usable prototype. This prototype was then iterated with domain experts who ensured that the interface and tests scenarios were realistic enough to guarantee the involvement of future users during testing.

At the end of the second step, the prototype considers all the extracted critical elements necessary for SA acquisition and is ready to be evaluated for its SA acquisition capabilities. This evaluation will validate the ability of the SASS to provide SA to the user.

II.3.4 Step 3: SASS validation

The validation of the SASS is performed through “human-in-the-loop” tests. This validation, following the human centered design paradigm, is obtained through user feedback. It focuses on the evaluation of the SASS tool through the vision of the future users. This validation is performed in two steps:

- Tests are then performed on the prototype by the users. These tests aim at studying the users’ activities as well as the reality anchors used for decision making.
- This activity analysis may highlight the lack of some reality anchors that will need to be part of the final SASS and, therefore, result in an iteration of the anchor elicitation and human-in-the-loop testing. This iterative process will be performed until all necessary reality anchors are implemented.

II.3.4.1 Stage 1: User testing

During the testing phase, the designer performs tests with future users following a pre-established protocol. Defining a protocol ensures that the tests are reproducible. It also ensures that the content of the test is controlled before launching the test. This protocol is defined in three main parts.

- The first important part is a training phase allowing the user to become familiar with the prototype that will be evaluated. The prototype presented, even if it is

based on current use SASS, will allow access to new information and may use new interaction techniques. These changes must be presented to the user during this training phase. There are three main ways to conduct this training:

- Tutorial: this training method will ensure that all possible information and actions (as thought by the designer) are introduced to the user. This method directs the user towards the goal by letting them use the tool.
- Exploratory freedom: this training method provides the user with a checklist of actions and information to be found in the tool. This technique is less rigid and offers more freedom to the user, but it takes more time than the tutorial method.
- Demonstration: this training method introduces the user how designers use the tool and can be done quickly. However, this solution does not provide practice to the user and might influence how the user will perform the scenarios.

During this training phase, a specific scenario can be designed to ensure that the main commands of the tool are used. However, this scenario should not use situation like those that will be used for testing in order not to bias the user.

In a human-centered logic, the exploratory solution is to be encouraged but, in case of limited time, a tutorial can be used as a degraded mode to ensure a faster training without influencing the user's activities.

- The second important part of the test is the test by itself. The test should be performed in a controlled environment, a dedicated space, to ensure the repeatability of results. During the testing, scenarios will be presented to the user and its activity will be recorded.

Testing scenarios should be designed to provide different information and expose the user to different situations. Presenting the user with different types of situations will allow multiple behaviors to emerge from the results. This will also provide insight into the possible relationships between the situations and the information the user is viewing. During testing, the use of the "thinking aloud" method and the recording of the user's voice will both give an understanding of the user's activity and provide the user with flexibility for actions or information not available in the prototype. Identifying the reasons behind activities might provide knowledge about unexpected behavior in the situation awareness assessment to be performed later. As part of the rationale for the activity, when implementing the prototype, there may be actions or information that cannot be implemented. This will also allow for re-evaluation of the previous anchor elicitation step and ensure that the future iteration(s) of the tool provide all the necessary information.

User activity should be recorded during the test to analyze the usability of the tool. Recording of user activity can be done by:

- Recording of clicks and pointer position in the tool: this solution must be integrated into the prototype and therefore must be implemented during

- prototype development. In the case of early prototyping and short development time, this solution might be too complicated to implement.
- Recording of the screen by integrated software or with a camera: this solution is cheaper financially and in terms of implementation time. However, the quality of the recordings will affect the quality of the results and this solution must be integrated in the test protocol. The processing of the resulting videos may take longer to analyze than the integrated solution.
 - Using of eye-tracking to record the user's observation habits: this solution provides results concerning attention and cognitive load. However, this solution is not free of charge and the analysis of the results is time consuming.
- The last part of the testing phase should be a debriefing with the user. This debriefing step will allow to collect the user's thoughts on the testing phase, to explain the reason for the choices made during the scenarios and capitalize on the user experience feedback.

This phase can begin by asking the user for feedback on the tests, the process, the content, the problems they encountered. This will inform the designer about how the tests affected the user and generate knowledge to correlate with future behavior analysis and possible mistakes made during testing. Once the user's feedback is expressed without bias, the scenarios and their intents can be presented to the user. The user is invited to react to express their experience with the scenarios and provide more detailed, scenario-centered, feedback explaining their activities. If subjective evaluation techniques are used, the debriefing phase can capture the user's feelings related to this evaluation to better highlight the user's subjective evaluation.

This three-parts testing stage should provide many results regarding user behaviors while using the prototype. It will allow the prototype to be analyzed and adapted with respect to its design features and its ability to deliver SA.

II.3.4.2 Stage 2: Situation awareness evaluation

Evaluating the effects of the prototype on the users' situation awareness is the reason why the human-in-the-loop tests were conducted. Assessing situation awareness is a difficult task because it is an unconscious human phenomenon. There are different methods in the literature for assessing human situation awareness as presented in part 1 section I.2.4.

The RAM focuses on eliciting specific reality anchor and this human-in-the-loop testing is intended to ensure that the elicitation is correct. As we are not sure that the elicitation is correct and that no anchor is missing or not used it is difficult to base the evaluation on a define a fixed list of elements like needed for the SAGAT or SACRI. Thus, the use of SART seems logical to provide a picture of situation awareness in the different

scenarios based on expert users and not focus on an objective assessment of the quality of situation awareness.

To use the SART, it is important to relate the criteria to the expected values. On 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 another hand, the criteria regarding the user should be evaluated based on the awaited answers. For example, the spare mental capacity should be as high as possible to ensure that the user does not feel mental overload.

If the results do not align with the expected results, posttest interviews can provide light on the reason of the difference. Moreover, the experience feedback and activity analysis must be used to highlight miss used of the reality anchors and defined recommendation to improve their use to provide situation awareness to the user as intended.

II.3.4.3 Stage 3: Experience feedback analysis

Identifying the use of the reality anchors will enable to evaluate the first elicitation and ensure to correct any mishaps during the process. To identify the use of reality anchors in the situations, a focus on experience feedback information is proposed in the RAM. Industrial experience feedback is known to provide activity-related knowledge (Ruiz et al. 2014). As such, it provides a medium for situation description. This situation description must be performed through the reality anchors. It makes experience feedback a great tool to evaluate the use and importance of elicited anchors. Following this idea, three types of experience feedback were defined to evaluate the reality anchors used to describe a situation.

The first type of experience feedback is based on shift books used in the oil-and-gas domain. Shift books are used for control room operators to report on the situations experienced during the shift to next shift operators. It is simply a free expression support whose purpose is to record the situation experienced and share it with other users. It contains expert vocabulary and focus on the most important information needed to understand the situation without sharing the most detailed information and reasoning. This experience feedback will provide the reality anchors needed for basic understanding of the situation and thus be considered a major concern for the user's situation awareness.

Second type of experience feedback is more directive feedback with three categories of questions.

- A description of the situation is requested to identify the main reality anchors used to describe the situation. This part of the feedback focuses on the perception level of situational awareness.

- The user is asked to analyze the situation. The objective is to encourage the user to provide information related to their understanding of the situation.
- The action taken to resolve the situation are explained. This part is intended 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 reality anchor in the three levels of the situation awareness process.

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

The three types of experience feedback are used in different scenarios and are defined so as not to influence the user's expression of the situation. To ensure to no bias is introduced, the first type of experience feedback must be used before the second one and the second before the third so as not to influence the user's free expression.

Based on the experience feedback forms, it is then possible to identify the reality anchors most important to describe a situation thanks to the free experience feedback form and those that are used as details. This hierarchy in the reality anchors priority enable to define which anchors are to be highlighted in the interface to make them available more quickly.

II.3.4.4 Stage 4: Activity analysis

From the activity recorded during the test phase, whatever the solution used to record the activity, the knowledge of the information consulted by the user during the scenarios is capitalized. In the case of eye-tracking, the user's point of interest will show the information consulted. In the case of the recording of the internal pointer, the information pointed to and the clicked menu consulted by the user will give indications about the information used. In the same way, the recording of the screen activity will provide information on the information selected by the user.

Once awareness has been gathered, reality anchors used during the tests can be elicited and missing anchors can be identified through the voice recordings and debriefing phase. The process of acquiring situation awareness can also be compared to the results of the interviews. This activity process, once compared, can provide light on missing reality anchors and enable to define a final decision process for the user

tasks. The process may also show emerging behaviors and sub-task division enabling a better understanding of the human decision-making process. Moreover, it can point the useless anchors to be removed to avoid overloading user interface.

In an iterative way, missing and unnecessary reality anchors can be added to the SASS to design a tool that offers a better integration of human needs. The newly updated tool can be tested following the same protocol to ensure the presence of all necessary reality anchors.

The iterative process should be stopped when all reality anchors are implemented, and the tool is defined as enabling user situation awareness and decision making.

Conclusion

Human Systems Integration design methodologies have been shown to focus on ensuring the usability of designed systems. Within these methodologies, some focus on addressing human situational awareness. However, none proposed a detailed process for identifying user needs related to SA and assessing the impact on the user through human-in-the-loop testing. To address this gap, the Reality Anchors Methodology was defined. This methodology focuses on eliciting reality anchors as resources used by humans to gain situational awareness and implementing them in the Situation awareness support system to ensure human situational awareness when using this tool. This methodology is based on three steps: (1) task analysis, (2) human-in-the-loop testing and the (3) activity analysis.

Task analysis focuses on acquiring knowledge about user tasks through regulatory study and interviews to identify the reality anchors needed to perform user tasks. Human-in-the-loop testing focuses on using expert user knowledge in a simulation to identify missing and unnecessary reality anchors implemented in the tool while monitoring the tool's ability to provide situational awareness. Finally, activity analysis provides knowledge about the use of reality anchors and allows iteration on the situation awareness support system to define a tool that integrates humans needs and supports decision making.

This methodology was applied on an oil-and-gas use case to be validated. This application is presented in the following section.

Part III: Oil-and-gas use case: Decision Making in the Event of a Gas leak on an Offshore platform

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Introduction

The Reality Anchor Methodology (RAM) focuses on identifying situational elements in the decision-making process to ensure that the user acquires situation awareness. This methodology was explained in the previous part.

This part focuses on the application of the proposed methodology to an oil and gas use case (applicable to new energies activities) which has been defined by the R&D Safety theme of TotalEnergies company. One of the R&D projects is focusing on developing and qualifying new detection technologies and new modeling tools to anticipate or respond faster to events in standard or remote operational conditions. The use case is therefore related to a realistic industrial context and focuses specifically on decision-making regarding gas leak management.

The methodology has been applied to design a Situation Awareness Support System (SASS) intended to assist operators in monitoring an industrial process and particularly potential gas leaks. Detailed results and the approach used to obtain them are described in this section starting with the study of the company rules. We firstly performed interviews with company operators to study their decision process and identify reality anchors. We secondly developed a prototype and designed and performed experimentations with company operators, under the form of human-in-the-loop simulation. Finally, we reevaluate the prototype and the defined reality anchors to update the tool.

III.1 Use case

“Safety is not a new field but an inherent part of industries worldwide” (Pathak and Ashutosh 2019). TotalEnergies R&D division focuses, among other themes, on continuously improving safety on all its industrial sites. One of the safety R&D projects is related to improving decision-making in downgraded situations such as when a gas leak occurs for example. A downgraded situation is defined by the company as “any abnormal situation where the installation is operating outside its design concept, resulting in an increase in operation-related risk.”. In addition to testing, qualifying and deploying new leak detection technologies, this industrial research program seeks to evaluate the impact of these new technologies on control room operations and operators (FONCSI 2020).

To build 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,
- (3) the downgraded situation on which the decision would be made.

Moreover, several requirements have been defined to guarantee both industrial consistency and scientific relevance to the use case:

- To ensure a realistic behavior from operators, the chosen site must be a fully representative oil-and-gas site. TotalEnergies provided layouts and process information from an operational Floating Production, Storage and Offloading facility (FPSO) and thus oriented the site type choice. The selected site includes all the main process units that company operators are experienced in. To simplify the use case in anticipation of a prototype implementation, the choice has been made to select only two process units and to focus on a two stages separation process. A separation process aims at separating different fluids (gas, oil and production water for example) using their different density. This process includes the use of two separators operating at different pressures (huge fluid tanks) that are fitted with multiples flanges that have been identified by previous studies as part of the equipment the most prone to leak. This process has been modeled in the prototype and the physical part of the FPSO where the separators are located has been identified and virtually equipped with industrially relatable sensors and information.
- The unmanned/remote configuration (Munoz, Bartoli, and Macrez 2020) of the site was chosen to anticipate industrials questions related to possible future exploitation configuration and to discourage operator from using other information than those provided by the control room tool (system vs human). Indeed, current operation modality uses operators on site or "field operators" to perform regular surveillance and maintenance. This operating philosophy have encouraged control room operators to ask information to field operators. The goal of using a digital twin in control room is to provide real time and all pertinent information needed to the user. The choice has been made then to cut the operators from their habits to rely on field operators and to encourage the single use of the digital twin.
- To capitalize on the R&D project currently studying gas leaks detection optimization, the choice has been made to focus on this specific downgraded situation management. Gas leaks are currently detected using fixed sensors that monitor the concentration of gas in the air at specific locations. The use of new acoustic sensors enables to detect and localize leak sources making early detection a fact. Early detection of gas leaks enables control room operators to take decision and react before triggering of automatic safety actions impacting the process operability and generating unit depressurization by releasing gas inventory to the flare. Both safety and environmental concerns can be treated at the same time. The studied decision-making process is therefore an individual process that enables this study to focus on solitary decision making.
- The gas types were selected to be methane (CH₄), as it is the major gas present on the oil-and-gas sites, and H₂S, as it can sometimes be present and is toxic to humans. Gas detection is currently mostly monitored thanks to fixed concentration

sensors that enable to identify gas concentration in the air. Two types of gas are monitored by these sensors, flammable gases like CH_4 , and toxic gases, like H_2S . Gases become flammable in a range of concentration in the air. Toxic gases become toxic to human from a certain amount of gas in the air. To prevent damages to humans and installations, automatic safety actions are implemented on oil-and-gas sites. Once a detector registers a certain amount of gas in the air, this can trigger the automatic actions (evacuation alarm, process shut down...) and a team of experts is put into action to solve the problem.

To precise the scope of the methodology application, the use case selected for this study is based on a Floating Production Storage and Offloading facility (FPSO) of TotalEnergies company called KAOMBO (see Figure III-1).

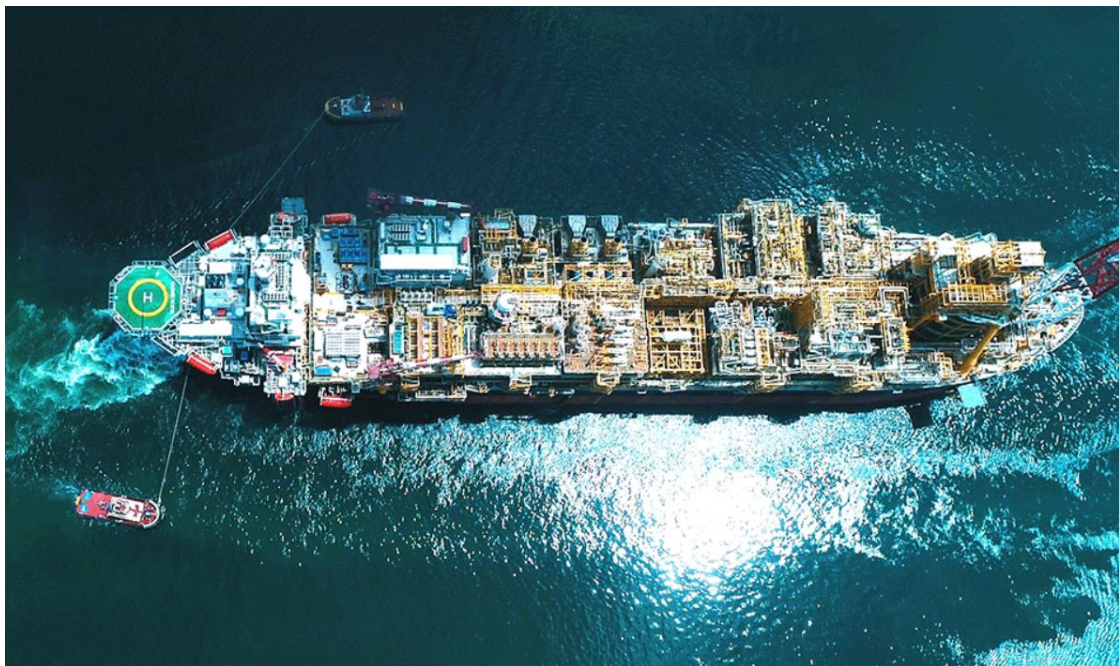


Figure III-1: Aerial picture of the KAOMBO Sul FPSO during its transportation to coast of Angola. (Source: totalenergies.com)

The KAOMBO site is composed of 59 wells linked to two FPSO (KAOMBO Norte and KAOMBO Sul). These sites are extracting an oil/gas mixture that is separated on the FPSO and then send to shore. Anchored in the middle of the ocean in deep waters, those sites are part of the most recent sites of the company and present specific life conditions (isolated location, fighting weather conditions, etc.) that make them a good representation of the domain challenges. Therefore, it was chosen to create a fictive FPSO, called KOMBA, that has the same structure as KAOMBO Sul FPSO and uses a new leak detection technology, the acoustic detection.

FPSO are structured in different sections or fire zones (see Figure III-2). For this study, the control room operator was in charge of the separation process located in section S7 of the FPSO.

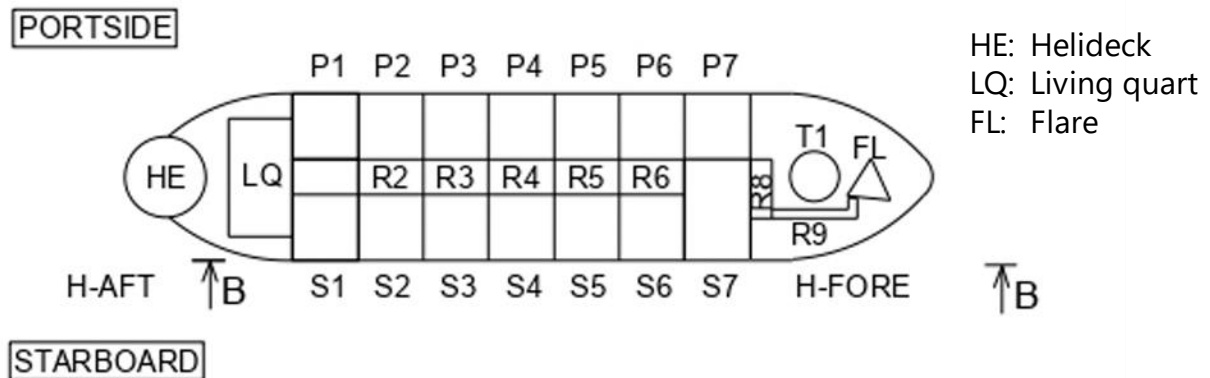


Figure III-2: Organization of the KAOMBO Sul FPSO.

III.1.1 The process

The process chosen for this study is a simplified 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 fitted with flanges that have been evaluated in an internal study as the origins of most gas leaks. The use of the separation process is therefore coherent both in term of anomaly realism and operators work conditions.

This process is composed of a high-pressure stage and a medium pressure stage.

III.1.1.1 High pressure (HP) stage

The HP stage process (see Figure III-3) is composed of a three-outlets separator, that aims at separating oil (in green), gas (in yellow) and production water (in blue), with the associated flowlines and control and isolation valves.

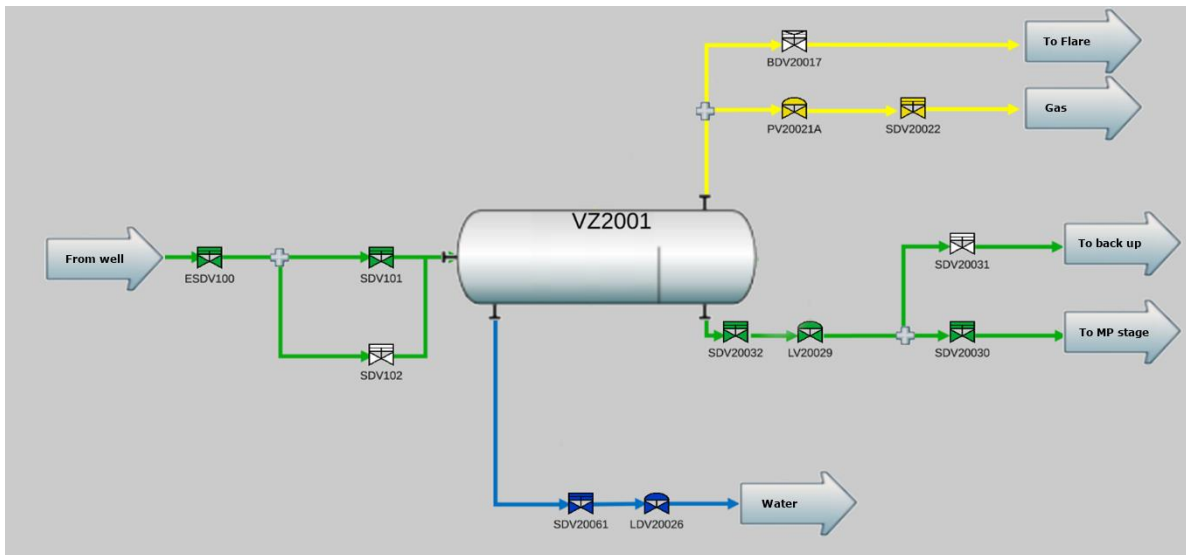


Figure III-3: High pressure stage process map.

Looking in more details at the process unit, the oil/gas mixture is sent upstream from wells to the separator through flowlines equipped with a set of Emergency Shut Down Valves (ESDV) and Shut Down Valves (SDV). Emergency valves cannot be controlled by operators and are actuated by the automated safety system called ICSS (Integrated Control and Safety System) based on the safety philosophy. Downstream of the separator, Pressure Valve (PV) and Level Valve (LV) are used to automatically maintain the pressure of gas and the level of oil and water in the separator based on a selected set up point. Finally, in case of emergency, a Blow Down Valve (BDV) is implemented to reroute the gas inventory in a safer place by sending it to the flare to be burnt.

In this process some alternatives solutions are proposed to the operator in term of leak control. If needed, the operator can switch the upstream SDV 20030 and 20031 and send the oil from the high-pressure stage to a fictive backup separator. However, the backup stage is not implemented and is only here as a possibility of action for the operator.

III.1.1.2 Medium pressure (MP) stage

The MP stage process (see Figure III-4) is composed of a two-outlets separator, that aims at separating the remaining gas from the oil coming from HP stage outlet, with its associated flowlines and control and isolation valves.

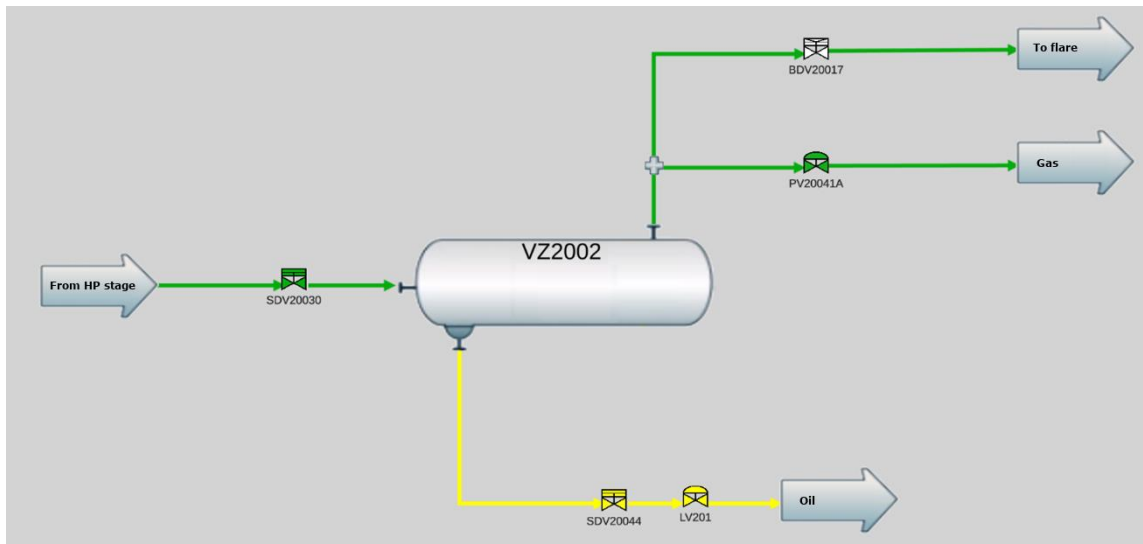


Figure III-4: Medium pressure stage process map.

The MP stage process is equipped in a similar manner as the high-pressure stage with a Shut Down Valve (SDV) isolating the oil inlet. Downstream of the separator, a set of Level Valve (LV) and Pressure Valve (PV) ensure to maintain the working values in the separator. A Blow Down Valve (BDV) is implemented on the gas outlet leading to the flare as the safety rules requires it.

III.1.2 The context

The process equipments are situated in the section S7 of the FPSO. This part of the FPSO is organized in three floors: (1) the process deck, (2) mezzanine deck and (3) upper process deck. In addition to the process equipments, those floors are equipped with acoustic sensors, standard gas concentration level sensors and Close-Circuit TeleVision (CCTV) systems. However, those systems did not appear in the layouts retrieved from KAOMBO site. For the sake of realism, those elements had to be implemented on the layout in accordance with regulations (except for the acoustic sensors that still under qualification) as if they were implemented in real life. However, no official instance from the company validated their position.

III.1.2.1 Defined captions

To identify the different sensors and equipment on the layouts, a set of captions was defined and used for this study (see Figure III-5). Following User eXperience design concepts and recommendations from Yumaneed¹⁵ company that has been commissioned by TotalEnergies to provide preliminary recommendations; every element was defined using different shapes and colors.

Gas concentration level sensors, also called Dräger sensors, are represented with a square and a logo showing a fire for flammable CH₄ and a skull for toxic H₂S. The color

¹⁵ <https://www.yumaneed.com/> (consulted last 04/08/2022)

of the square represents the status of the sensor: green if the sensor is activated, red if the sensors reached a predefined gas concentration threshold and grey if the sensor is inactive.

Acoustic sensors are represented using hexagons and a microphone logo. Their status is also represented through a color code. However, these sensors are used to point out leak position which is represented using a red circle on the layouts.

Equipment and their maintenance status is presented using grey diamond shape and a gear logo. Equipment with "late" maintenance (not performed at the exact planned date) is represented using a black diamond.

CCTV equipment positions on the site are represented with a purple tear shape.

In addition to those physical fixed elements, the layout enabled to show places where works are taking place based on the work permit database. Hot work permits (generating sparkles or flame and able to ignite flammable gas cloud) are represented with a yellow triangle and flame logo. Cold work permits are represented with a blue triangle and a snowflake logo.

	CH4 sensors		H2S sensors		Equipment maintenance info
	Active status				On time status
	Detection status				Late status
	Inactive status				Hot work permit position
	Acoustic sensor position				Cold work permit position
	Active status				CCTV position
	Detection status				
	Inactive status				
	Acoustic detected leak position				

Figure III-5: Captions used on the site layouts.

Those elements represent all the information contextualized on the layouts and are organized in the same way for each scenario.

III.1.2.2 Side view

On the side view, only the equipment and permits are represented (see Figure III-6).

Looking at this layout, it is possible to identify the HP separator as the bottom tank on the process deck and the MP separator as the top tank on the upper deck. A cold work permit icon can be seen as well on the mezzanine level.

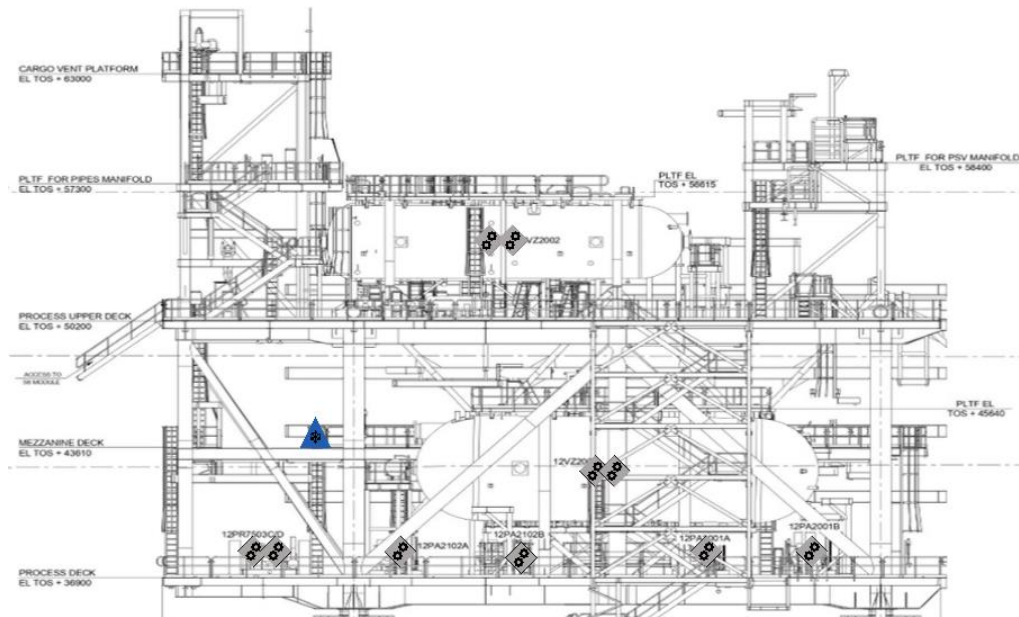


Figure III-6: Side view of the section S7.

III.1.2.3 Process deck

As it can be seen on this layout (see Figure III-7), the process deck of the section S7 does not only include HP separator. In addition to the HP separator, this floor includes another separator and a set of oil pumps. Each pump is monitored with a set of Dräger sensors (CH₄ and/or H₂S). Moreover, the separators critical points (inlet and outlet on the left and confined spaces between the tanks) are equipped as well with Dräger sensors. Three CCTV are made available on 2 corners of the floor. As for each floor, a set of two acoustic sensors are placed on the boundaries to cover the floor area.

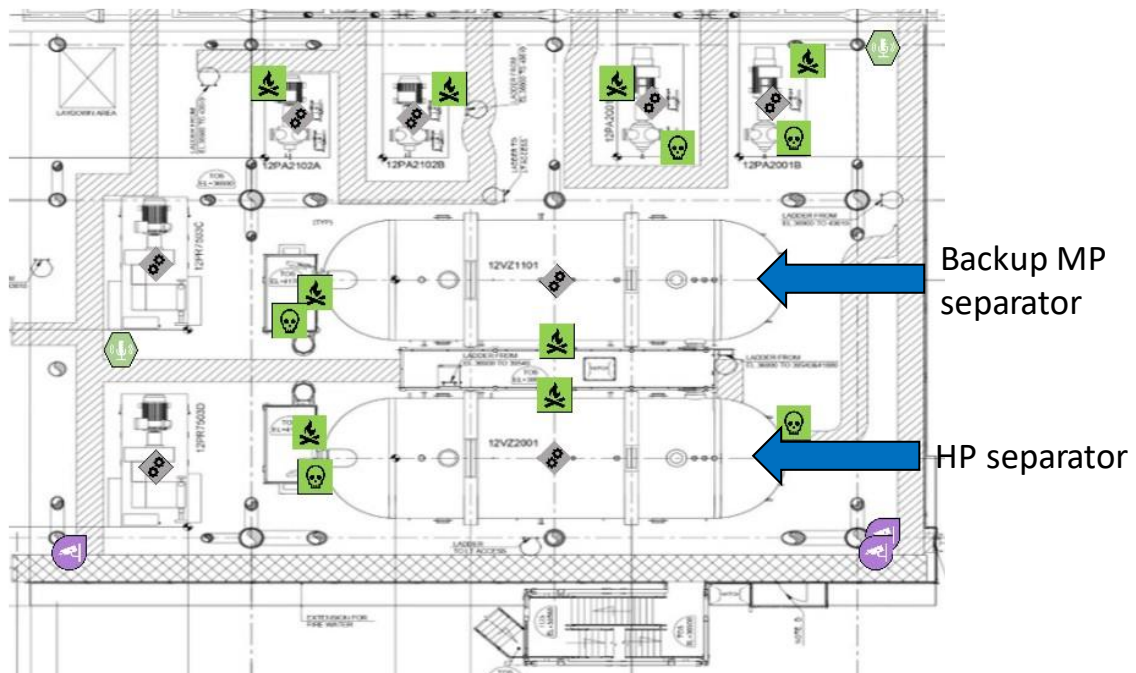


Figure III-7: Layout of the process deck floor.

III.1.2.4 Mezzanine deck

The mezzanine deck floor (see Figure III-8) is an intermediary floor between the process deck and the upper process deck that enables operators to access the top of the HP separator on the process deck. As it is an intermediary floor and that H₂S behavior (heavy gas) tends to lay down on the floor, no H₂S sensors were implemented. However, a set of CH₄ sensors were located at the top of the tank aperture (gas outlet) and on top of the pumps (pumps are critical equipments for gas leaks). As for every floor, two acoustic sensors enable to locate leaks. In correlation with the side view layout, a cold work permit icon is present.

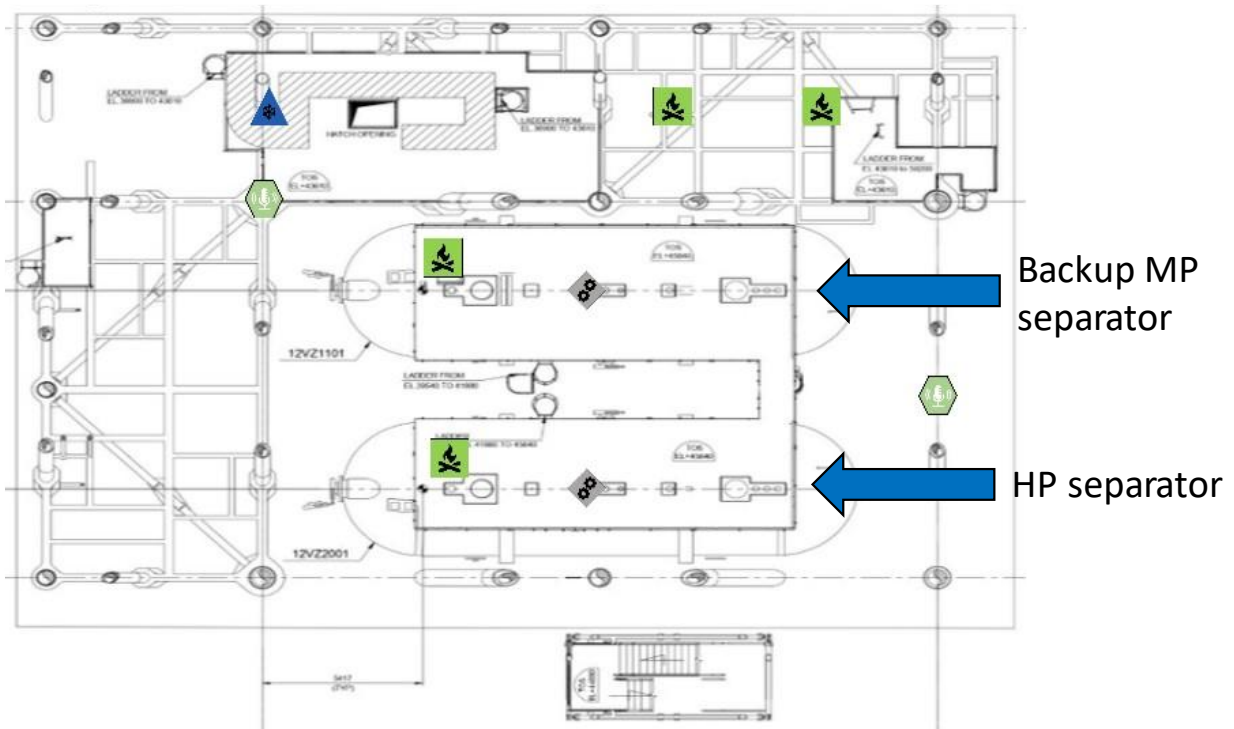


Figure III-8: Layout of the mezzanine floor.

III.1.2.5 Upper process deck

The upper process deck floor accommodates two separation tanks. The larger tank is the MP separator from the presented process. The second smaller tank is a low-pressure (LP) separator and is not part of the process imputed to the operator. This floor is equipped with both H₂S and CH₄ Dräger sensors that are placed at the inlets and outlets of the tanks as well as close to confined spaces between the tanks. As for every floor, two acoustic sensors are implemented to monitor the floor. A CCTV is also in place in a corner of the floor, enabling to look at the tanks.

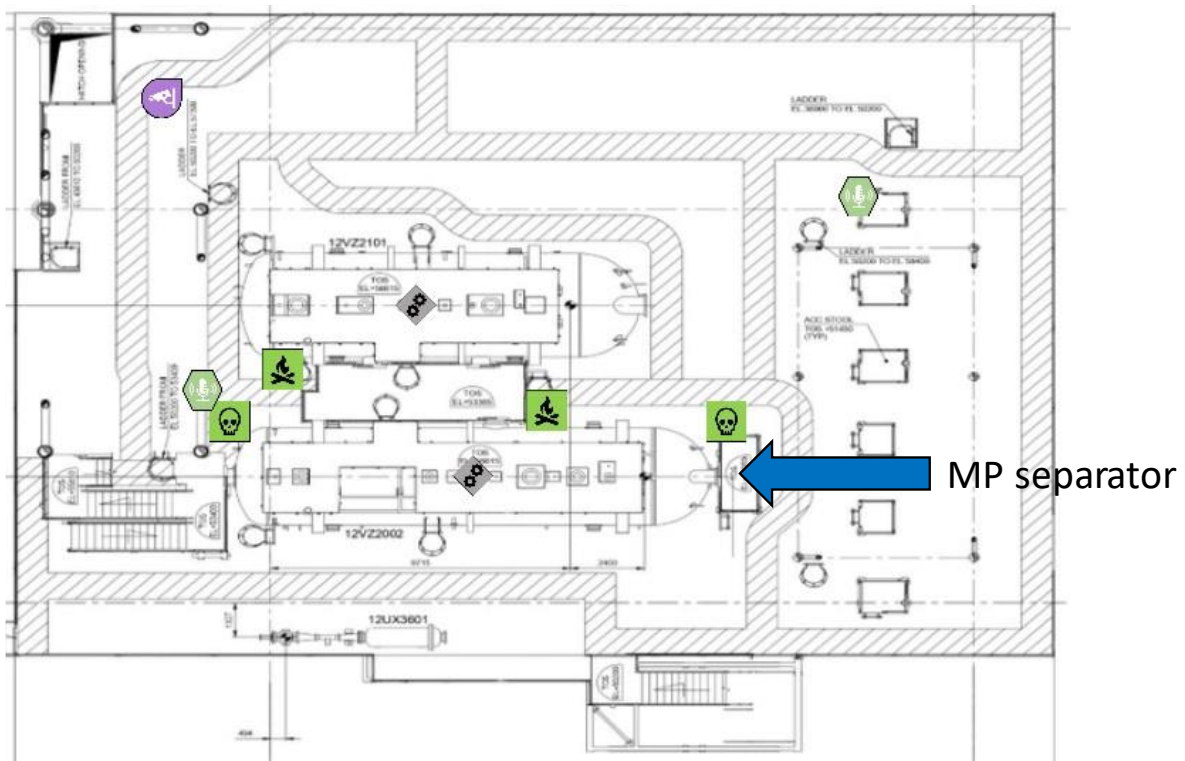


Figure III-9: Layout of the upper process deck floor.

III.1.3 Synthesis

The use case selected for this study is a fictive Floating Production, Storage and Offloading facility based on a FPSO vessel from TotalEnergies company. This study focuses on a two-stages separation process located in the section S7 of this FPSO. This two-stages process is a simple and usual process familiar to the operators that enables its realistic replication in a prototype. The process equipments are scattered on a three-floor section of the FPSO which had to be fictively equipped with sensors according to internal rules and procedures. All these features lead to a complex use case for the Reality Anchor Methodology (RAM) to be implemented with the aim at designing a control room operation system.

III.2 Reality Anchor Methodology (RAM) application

To validate the applicability and effects of the defined Reality Anchor Methodology, it has been applied to the previously defined use case. As mentioned in section III.1, the application of the methodology started with the study of TotalEnergies company rules and procedures regarding downgraded situation management followed by the interviews of operators on the subjects. Then, the results of the interviews enabled a cognitive function analysis and the elicitation of the reality anchors. Finally, human-in-the-loop tests were performed using the developed prototype. This application of the methodology enabled to reevaluate the prototype and the defined reality anchors.

III.2.1 Regulation study

The regulation study focuses on analyzing 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 types of relevant documents have been found in TotalEnergies EP referential:

- Company Rule (CR): HSE risk management in operation. It defines mandatory actions regarding qualified personnel, tools enabling information acquisition as well as work organization.
- General Specification (GS): Fire and Gas detection: this document explains and proposes qualified detection equipment, as well as the detection logic.
- Guide and Manual (GM EXP): 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 decision making.

Each document content is explained and developed in the following sub-section.

III.2.1.1 Risk management

The document related to risk management appoints the qualified personnel in form of responsible authority or domain experts to carry out a risk analysis and make decision upon work situations. This document also advises authority on ways to assess risks related to downgraded situation using three levels of risks:

- Level 1: first priority risks that must be reduced to level 2 or 3,
- Level 2: tolerable risks that are assessed As Low As Reasonably Practicable (ALARP - best common practice of judgement of the balance of risk and societal benefit)
- Level 3: broadly acceptable risks.

This level is defined by a risk matrix specific to the company that enables to identify the risk level based on severity of consequences and likelihood of occurrence of the incident. These factors are evaluated by a team of experts gathered for the specific analysis and treatment of the situation.

The work is organized in 4 steps:

- The preparation. During this step the preparation meetings take place, the information handovers are performed, the risk assessment is carried out and the corrective actions to be taken are identified.
- The approval. During this step the preparation is validated, and the work is authorized following the defined measures related to the identified risks.
- The execution. During this step the job is done

- The acceptance. During this step the work is verified and validated as being done "compliant as per request"

If the document related to risk management does not tackle the specific role of control room operators, it gives a clear overview on how decision is made in the field and at higher management levels.

III.2.1.2 Gas detection

The document related to fire and gas detection sets up the guidelines for design, selection, installation, location, and behavior of equipments and systems related to fire and gas detection. This document provides knowledge related to the detector and alarm systems that are mandatory and helps to better understand the technology used and the work performed by control room operators. The use case being related to gas leak, the study of this document focused on gas detectors.

The document explains which types of detectors can be used for which application and which type of gas. Therefore, if the fluid is a mix of different gas type, two types of detectors must be implemented. They have to be calibrated and maintained regularly to ensure a defined detection accuracy and reliability.

The location of the detector is based on safety studies, taking into consideration factors like site layout (possible congestion or accumulation area), prevalent and/or conservative weather conditions, and distribution of leaks configuration. In addition to the location definition, different detection technologies have been validated by the company based on specific applications and must be used accordingly.

The detection thresholds are also referenced in this document. Therefore, the alarms trigger is set to a certain amount of gas concentration in the air expressed in % of Lower Flammability limit (LFL). At the lower concentration threshold, the control room operator is informed through an alarm of the presence of gas and can act to stop the leak. However, on the upper concentration automated actions are activated and the operator lose its ability to act on the system. It is therefore important to work with alarm before the upper concentration threshold to study the operator behavior upon the control room system.

This document also informs on the implementation of detector layouts that should be used or known by control room operators.

As detectors have ability to shut down processes and with the possibility of false positive detection, a voting logic is implemented to ensure detection reliability. The voting logic means that multiples detectors are used in a loop to only trigger actions if enough detectors are activated at the same time. This highlights the need for operators to be informed of the voting logic and may influence operator in their personal alarm identification process.

This document gives a first look at the alarm system for gas detection and represents knowledge to be acquired by operator to work with gas detection systems. This document also enables to set the first layout of a context interface for a digital twin as it gives the rules related to detectors.

III.2.1.3 Management of downgraded situation

The document related to downgraded situation management gives the process for managing downgraded situations on the specific company branch related sites. This document highlights the best practices for risk assessment and the role and responsibility of all actors.

This document defines the concept of downgraded situation as stated in the introduction of section III.1. According to this definition, it confirms that the gas leak is a downgraded situation and, thus, should be treated following the given guidelines. However, the document details the process from the point of view of site authorities and not from control room operators. These guidelines will therefore be used to understand the global management logic and provide ideas and comparison points for the interviews protocol definition.

The document defines on-site actors as:

- The Site Environmental Safety Manager who oversees assessing potential downgraded situation, organizing the risk analysis, validating the situation, and ensuring its resolution.
- The operating authority and Health Safety Environment (HSE) superintendent who oversees reporting situations, contributing to the risk analysis, and implementing the defined measures.
- The other superintendents and supervisors who oversee reporting situation, assisting in the analysis if required, and implementing the defined measures.

Other actors, at base office, can be invited as specialists to contribute to the analysis.

Thus, multiple competencies and knowledge sources are necessary to ensure a decision. It is therefore possible that following a similar process, operators need information from multiple sources to ensure their early management decision.

The management process exposed in the document is defined in 6 main phases:

- Identification of the downgraded situation,
- Assessment of the initial risks,
- Identification of the mitigation measures and monitoring them regularly,
- Assessment of the residual risks,
- Decision to continue operations or not,
- Definition and implementation of corrective measures to return to normal operation situation.

Added to these phases, a continuous reporting task is performed.

These tasks are performed using different resources providing information related to the situation. These informations are potential reality anchors (see part 2 section II.1) to be used by control room operators as well. The process and the associated identified resources have been defined using the BPMN format. Figure III-10 show a simplified version of the process using features from the BPMN format.

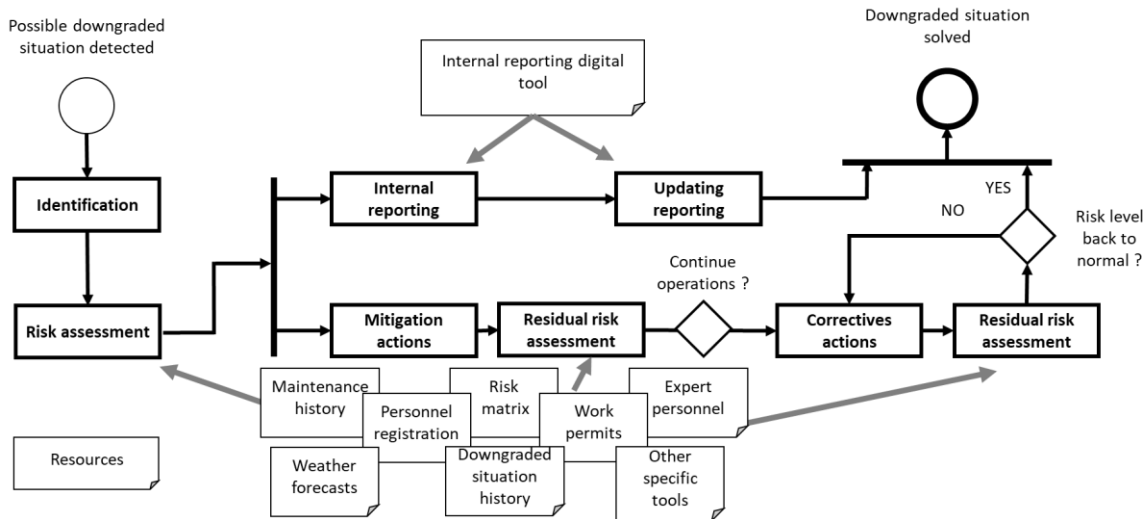


Figure III-10: Simplified recommended process of downgraded situation management.

This formalized process on downgraded situation management allows to identify the knowledge acquired related to general risk management and the gas detection logic. It also gives an overview of the job performed by control room operators. The following step will focus on ensuring a more detailed understanding of the tasks to be performed by control room operators using interviews.

III.2.2 Interviews with operators

The study of the regulations provided guidelines for understanding the decision-making process and identifying the tools and information used to make it. To validate and detail the users actual decision-making process, interviews are conducted, as work as imagined is known to differ from the work as done (FONCSI 2022; Hollnagel 2015).

The interview followed a semi-structured protocol defined to record user experience on domain-specific topics. This type of interview protocol gives the user the opportunity to speak freely about the topics and the interviewer the opportunity to ask detailed questions if necessary.

The transcripts of these interviews were then studied to define a decision-making process in the same manner as the regulation study.

III.2.2.1 The interview process

As introduced in part 2 section II.3.2.2 , the protocol followed for the interview is structured in five categories:

- The task performed,
- The tool used,
- The accessible information,
- The interaction with people,
- The acquired knowledge.

These interviews were conducted using a semi-structured interview protocol. The obtained results would not have been possible without the participation of members of the company who took time to participate.

A total of eleven male participants followed the interview process. These participants have 15 to 30 years site experience and have worked in five different positions:

- Field operators,
- Control room operators,
- Shift team leader,
- Production manager,
- Site manager.

This diversity of experience provided light on the control room operator work from different point of view.

Their experiences were acquired in different site types: on-shore, off-shore and deep off-shore operations in nine different countries. This diversity of profiles (operational and cultural) enables to ensure a global process definition that could relate to most operation situations.

The interview started with an introduction of the project and its goal. During this introduction the participant was invited to sign a consent form attesting of its will to participate and the respect from the project members of its results.

Then, the first questions were asked following the interview protocol. Every interview was recorded using a phone voice recording software. At the same time, notes were taken on paper to multiply the results gathering techniques and enable to react and create new questions if needed to ensure greater details in the answers. The use of the semi-directed interview structure showed a great flexibility in the ability to adapt the question to the user experience. However, this type of interview cannot be repeated exactly for each user and difference in answers emerge between each interview. For example, an operator who had worked in Africa was asked to describe in more detail the behavior differences he encountered while working there after he mentioned that differences were visible.

The non-repeatability of these interviews is partially solved by using questions categories. These categories enabled to get answers from the user in every awaited field. Therefore, if every interview didn't get the same level of details in every category, the users have expressed themselves in each field.

To enable an easier access to the interviews results, the recordings (a total of 518 minutes) were transcribed. The transcription is a time-consuming process (2 hours of work for 15 minutes of recording) but it enabled to access specific parts of the interviews more easily. Transcripts were first performed automatically using the transcription website: Happy Scribe. However, due to a high number of technical words used in interviews, a transcription validation has been performed afterward.

This process enabled to extract the users experience related to the management of gas leak in oil-and-gas site control rooms.

III.2.2.2 Results

The transcripts of the eleven interviews enabled us to gain understanding of the role of the control-room operator in the management of a gas leak.

The tasks performed by the control room operator are numerous (from monitoring process values evolution to contacting other operators), and the results showed that not every interviewee had direct experience with gas leak management. Operators with no experience were asked to consider similar downgraded situations in their experience such as liquid leak or compressor malfunction that both lead to decision-making from the control room operator.

Regarding the tools used by the operators, the main tools identified were CCTVs used to see what is happening on site, the internal communication system use to communicate with staff on site, or shift books that contain information about past shifts. However, the interviews identified a multiplicity of site-specific and non-generalizable internal tools, such as Microsoft Excel spreadsheets or maps depicting vessels in the site area. These tools were not considered in the final decision-making process. However, they should be considered necessary for implementation in future site-specific digital twins as the information in these tools may be needed by users in the specific environment surrounding the site.

The information accessed was directly dependent on the tools available to users. However, some information was described by users as potentially useful, such as equipment maintenance status, or site weather, but was not used due to time constraints. Therefore, this information was considered to be implemented in future control rooms, as the time constraints should be reduced in the newly designed tool.

The interaction between control room operator and other operators during the management of gas leaks can be classified in two types:

- The first regroups interactions used to acquire information. These interactions are most often due to a lack of knowledge or a distance from the situation. Identifying these interactions was important to identify the reality anchors to which this interaction gives access.
- The second regroups interactions used to transmit information. These interactions occur at the end of the decision-making process and mark the commitment to an action, or the authorization routine as seen in the general model of strategic decision-making (See part 1 section I.2.1.2).

The last category of interview questions was designed to identify the means by which operators acquired their knowledge. Results showed that a significant amount of the knowledge was passed down by more experienced operators and through field experience. This reinforced the validity of the interview process to acquire operator knowledge, as we are collecting knowledge from operators the way they do. However, training and simulations appeared as part of the process as well. The simulation-based learning process reinforced the idea of using human in the loop simulation for later design methodology step (see part 2 section II.3).

The results presented at the beginning of this section are complemented by the definition of the gas leak management process by control room operators. The process extracted from the interview results (see Figure III-11) is a five-step process:

- Once a leak is reported, by the alarm system or directly by field operators, the control room operator tries to validate the leak presence. This is done mostly by accessing information sources different from the initial detection source like another sensor detection, process KPI to see possible variations, CCTV images to see air flow deformation or by asking a field operator to go see at the possible leak location.
- The leak being validated, the control room operator will ensure field operators' safety by locating close personnel if any and identifying the leak characteristics (gas nature, flow rate, etc.). Operators presence is identified mainly through work permit database (description of work to be done on site) or directly through CCTV images. The operators are then contacted through the internal communication system or by the activation of the specific on-site alarm.
- Once humans are safe, the possibility for partial shutdown of the installation is evaluated based on the leak and process characteristics.
- If possible, the control room operator will engage mitigation measures by contacting expert personnel and informing the shift team leader.
- Finally, the situation will be reported to next shift operators team using the shift book.

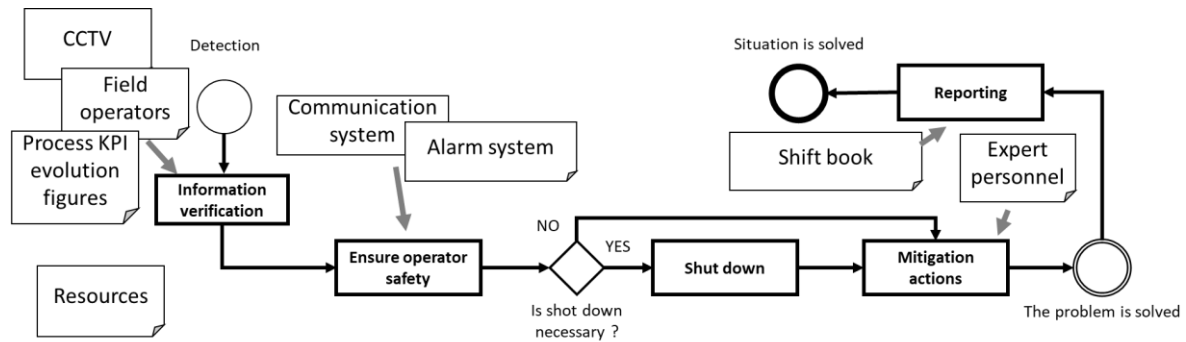


Figure III-11: Simplified operator's process gas leak management.

Comparing the two obtained processes, differences due to work situation can be identified.

First, due to time constraints differences, the used information sources are different. This is in line with the information obtained during the interviews related to accessible information. These differences might be narrowed thanks to the ability of digital twins to contains information and knowledge (see part I section I.4) in a global tool.

Differences also appear in the order and form in which the reporting action is performed. As anomaly must be treated swiftly to avoid possible escalation, control room operators need to react in less than 10 to 15 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 and not during. Moreover, the reporting is done in a free writing format as opposed to the directed reporting form of the global management process.

Furthermore, similarities appeared in the form of the main activities performed showing a global management logic with a verification of the information, actions to solve the problem and a report for other to be informed. This confirms the choice to use a digital twin to enable a more complete situation-oriented decision-making process. To identify in more detail the situation-oriented elements used by operators to acquire situation awareness, a cognitive function analysis is performed on the identified control room decision-making process.

III.2.3 Cognitive function analysis and reality anchor elicitation

Once the tasks to be performed have been identified, the cognitive function analysis paradigm (Boy 1998) is used to identify the reality anchors used by the operators to acquire situation awareness and make decisions. These will then be implemented in the digital twin to ensure its ability to provide the necessary elements to users to acquire situation awareness.

The cognitive function analysis aims to identify cognitive function used by humans to perform tasks. These functions are defined using a name, a context, and resources both physical and cognitive.

In the case of this study the tasks to be studied are the five tasks identify in the previous step (see III.2.2.2):

- Verifying the information,
- Ensuring the humans safety,
- Evaluating the necessity for a shut-down,
- Engaging the mitigation measures,
- Reporting the situation.

These macro-tasks can be subdivided into more precise tasks that are easier to study. For example, the task "verifying the information" can be sub-divided into the more detailed tasks:

- Acquiring the information,
- Identifying possible process variations,
- Communicating with the operator on the field,
- Concluding on the information validity.

This decomposition can be obtained through an iterative process until the level of tasks detail enables the designer to identify the cognitive function used. Going into more details in the task definition is performed by answering the question "How does the operator performs this task?". During this process, new sub-tasks will be defined and the organization of the tasks will evolve as the details are added. This study found that a sufficient level of details can be obtained once tasks are separated due to different context usage. For example, if the tasks require searching for information, a sufficient level of detail would elicit tasks for each piece of information to be searched. An example of this process is shown in Example III.1.

Example III.1: Application of the reality anchor elicitation.

Taking the example of "verify information" task (see Figure III-12), the first iteration brought to light four sub-tasks that are: (1) acquire information, (2) define base line, (3) compare the base line to the current status and (4) validate the alarm. During the process, new tasks emerged at the end of the iterations like "identify the nature of the problem" coming from the acquired information sub-task. Some functions were not required to undergo four iterations, like "identify the alarm signal" sub-task. Some others were reordered due to new details being implemented like "identify the deviation in the process" sub-task. And finally, tasks were defined up to the specifics of the resources to be tackled, like "ask about the sounds" sub-task.

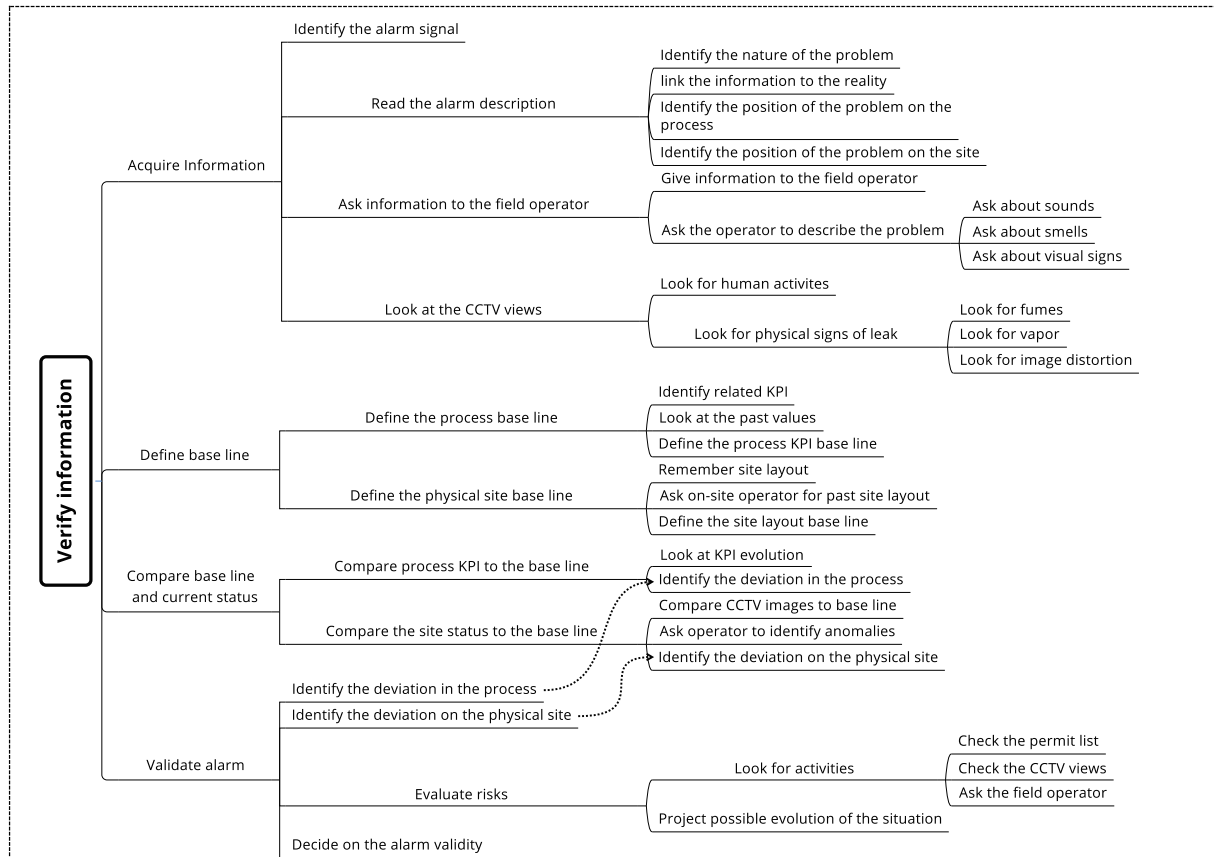


Figure III-12: "Verify information" sub-tasks definition iterative process.

This study has reached the required level of details after 4 iterations. At the end of the four iterations, the four initial sub-tasks are decomposed into 29 more detailed sub-tasks that can be associated to cognitive functions.

Once the tasks are sufficiently detailed, cognitive function can be defined and the associated resources can be elicited.

The elicitation of the cognitive function aims at defining for each function (1) a name, (2) a context and the associated (3) physical resources and (4) cognitive resources. The name of the function is usually the same as the task, enabling to understand the goal of the function. The context is "a context of which defines the constraints that bound the task domain" (Boy 1998). The resources are what is needed to achieve the transformation from task to activity. The physical resources are physical elements necessary to perform the task. The cognitive resources are non-tangible resources needed to perform the task. The resources used by cognitive functions can be tools, data, software, or cognitive functions themselves.

Looking into the resources, information originating from the reality to enable the user to acquire its situational awareness are called reality anchors (see Part 2 section II.1). Identifying those reality anchors enable to set up guidelines for information implementation in the SASS.

Following this decomposition and taking the example of “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 alarm audio signal (physical),
- A visual variation on a physical system (physical),
- The function “remembering the alarm signal types” (cognitive),
- The function “earing audio signals” (cognitive),
- The function “seeing a visual signal” (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 reality anchors can be defined as an audio alarm signal and a visual alarm signal. As reality anchors, these signals enable the user to identify that a sensor or more have changed status and have detected an anomaly in the situation.

At the end of the analysis of the 29 cognitive functions previously identified, a total of 29 reality anchors were discovered (see Table III-1).

Table III-1: Reality anchors list.

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

To ensure the operator ability to perform its tasks with a situation awareness, those reality anchors had to be provided to the user of the digital twin. Next step of the methodology focuses on implementing those reality anchors in a prototype to enable human-in-the-loop testing.

III.2.4 Human-in-the-loop testing

During this step, three main activities were performed. First, a testing protocol was defined to evaluate the effect of the reality anchors on the user through the digital twin. This protocol aims to define the scenarios on which the user will be tested, to choose a method to evaluate the user's situation awareness, and to ensure that the reality anchors are used by the operator. In a second time, a prototype must be implemented with the reality anchors and be able to follow the defined protocol and its different scenarios and evaluation methods. Finally, the results of the testing are

analyzed to extract the conclusions and recommendations to iterate on the digital twin, and to ensure its ability to support the operator situation awareness.

III.2.4.1 Test protocol

The test protocol enables to define how the user testing phase will be conducted (see Figure III-13). This is a first step to build the base of the testing and ensure the validity of the evaluation. The protocol defines the training phase choice to enable the user to familiarize with the prototype. In this use case, the choice has been made to define five scenarios to immerse the operator in different realistic situations. As part of this protocol, the evaluation techniques (presented in part 1 section I.2.4) used to evaluate the impact of the prototype are defined as well.

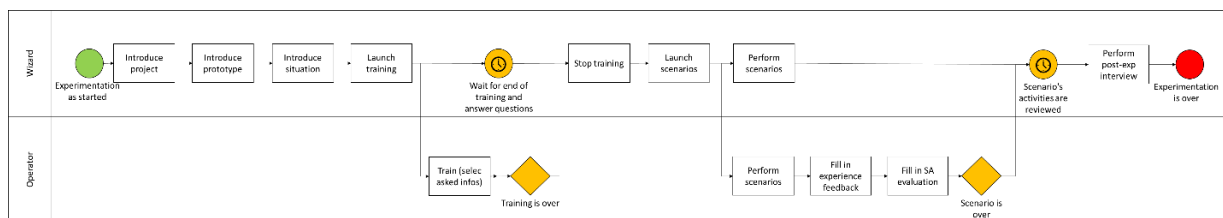


Figure III-13: BPMN model of the user test.

Training

The training phase aims to familiarize the user with the prototype. Multiple choices are possible to structure this phase as exposed in part 2.

For this use case, the choice has been made to present a checklist to ensure the user have time to explore the tool. This phase aims at identifying missing elements and implementing user needs in the digital twin.

The defined checklist is divided in three sections that focuses on each interface (one for the process and one for the context) and on the link between the two. To ensure learning, every type of interactions with the prototype were asked to the user through the checklist. These actions ensured to show the user how to access information as well as where and which information are accessible to him.

Regarding the process interface, nine actions were asked from the user:

1. Acquit alarms
2. Show PV20021A valve details
3. Set PV20021A valve set point to 21 bars
4. Switch LV20029 valve to manual
5. Rise LV20029 valve set point to 1%
6. Close SDV20061 valve
7. Open SDV20061 valve
8. Show high pressure separator pressure value
9. Show medium pressure separator internal values (pressure, liquid levels, etc.)

Regarding the context interface, fourteen actions were asked from the user:

1. Select section S7 on the site map
2. Hide/show the caption
3. Switch section view
4. Show information related to detected leaks
5. Hide/show the gas leak sensors icons
6. Show permits list
7. Hide/show permits icons
8. Show equipment list
9. Hide/show equipment icons
10. Show weather information
11. Hide/show the compass
12. Show CCTV streaming
13. Hide/show CCTV icons
14. Show icons details for CCTVs, acoustic sensors, Dräger, equipment and permits

Regarding the interaction between the two, it was asked to the operator to identify same elements on the two interfaces to ensure its understanding of the link between the process and the site layouts.

During this phase every question from the user regarding the information in the prototype are answered. Asked question often regarded the limits of the prototypes like "where can I find process trends?" or "are the CCTV images going to evolve?". Moreover, first recommendations from users on the prototype design are gathered as well. These recommendations regarded the too small size of the alarm information and dedicated space or the lack of process trends in the prototype.

Scenario choice

The scenario definition and selection has been an iterative process. It aims at defining a set of scenarios to be played during the testing to identify specific user behaviors.

The scenario definition started with the selection of the scenario parameters and their value range. In this use case the first identified parameters are linked to the situation definition and are:

- The leak intensity, as a larger leak will have more risk to impact its environment. The leak intensity can go from small (without visible impact on the process values) to medium (with a visible impact on the process values). Large leaks are not considered as such as they would trigger too quickly the automatic shutdown answer from the automated safety system.

- The gas type, as some gases are toxic, flammable or none of those and therefore impact their environment differently. For this iteration, the selection was done between hazardous gases (CH₄ – flammable or H₂S – flammable and toxic) and a nonflammable nontoxic gas (CO₂ – asphyxiating).
- The declared work permit on site, as the presence of human on site is a critical factor identified during the interviews. The permit, if any, could be close of the point of interest (leak area), far from it or have not started yet.
- The maintenance status on the surrounding equipment, as it is supposed that a late maintenance would provide easier confirmation that a problem might have truly happened.
- The weather, as weather condition might impact gas leak identification. The weather can be cloudy, sunny (making visible vapor detection harder), rainy (make the gas cloud go closer to the floor) or evolving.
- The presence of wind, as the gas cloud will evolve differently depending on the wind direction and speed. The wind was defined as being nil (providing no dissipation), calm (providing few dissipation), strong (proving fast dissipation) or evolving.

These parameters enabled to define the risks on site, based on the knowledge acquired from the interviews with the operators, and to identify different combinations leading to different uses of the reality anchors. Following this, twelve scenarios were defined as showed in Table III-2.

Table III-2: First scenario table.

Scenario	Leak intensity		Gas type			Permits				Maintenance				Weather			Wind			Risks involved
	Small	Medium	CO2	H2S	CH4	None	Far	Close	To Be	None	Old	New	To Be	Sunny	Cloudy	Rainy	None	Calm	Strong	
SC0	Small		CO2			-				-				-			-			
SC1	Medium		H2S/CH4			None				None				Cloudy			Calm			Quick toxic/flammable cloud creation
SC2	Small		CO2			None				None				Cloudy			Calm			Slow creation of a CO2 cloud
SC3	Medium		H2S/CH4			Close				Old				Sunny			None			Close operators' intoxication, cloud inflammation if use of hot tools or sun reflection
SC4	Medium		CO2			Close				New				Rainy			Strong			Quick CO2 flow creation close to the floor
SC5	Small to Medium		-			To be				None				Sun to Rain			None to Strong			Quick reaction and don't follow leak evolution
SC6	Leak 1 + Leak 2		-			To be				None				Sun to Rain			None to Strong			High focus on the first leak and forget the second one
SC7	Small		CO2			None				None				Cloudy			Strong			Small CO2 flow dissipation
SC8	Medium		H2S/CH4			None				None				Cloudy			Strong			Moving toxic/flammable gas cloud
SC9	Small		H2S/CH4			None				None				Sunny			Calm			Slow toxic/flammable gas cloud creation
SC10	Small		CO2			Far				To Be				Cloudy			Strong			Slow moving CO2 flow with person on site
SC11	Small		H2S/CH4			Far				To be				Sunny			Calm			Personnel that will come soon and risk intoxication or inflammation of the gas cloud

These scenarios were defined as an exploration of possible scenarios. Their validity from the domain point of view was questioned with experts. After discussing the

scenarios, the choice was made to define new scenario parameters. The parameters were chosen among the list of reality anchors defined previously (see section III.2.3). Table III-3 shows these parameters and their definition domains.

Table III-3: Scenario parameters and their range.

Parameters	Possible values	Description
Leak position	Top of equipments	Leaks from equipment top are more likely to take wind
	Between equipments	Leaks between equipment are more likely to concentrate fast
	At equipment extremity	Leaks at equipment extremity are at human levels and are likely to be exposed to wind
Leak intensity	0 kg/s	The leak is small enough that the process is not impacted
	2 000 kg/s	The leak is medium and the process values will be impacted in 10 minutes
	20 000kg/s	The leak is large and the process is directly impacted but small enough to not start automated safety measures
Gas nature	CH4	The gas nature was chosen to be CH4 in every scenario
Impacted sensors	No sensor	No other sensors than the acoustic ones are detecting the leak. This scenario does not provide confirmation
	One CH4 sensor	A sensor close to the leak is activated which act as a confirmation
	Three CH4 sensors	Three sensors are activated one after the other showing a cloud path and fast evolving rate
	Repetitive acoustic detection	The acoustic sensors goes back and forth detecting and not detecting
On-site permits	None	No work is performed on the section at the moment of the alarm
	Cold/close	A cold permit is in progress close to the leak
	Cold/far	A cold permit is in progress on another level of the platform
	Hot/close	A hot permit (possible flame) is in progress close to the flammable gas leak
Maintenance status	Ok	Maintenance have been performed in time and are not new
	Late	The maintenance is late on the impacted equipment
Weather	Cloudy	The sky is cloudy and thus does not impact the situation
	Sunny	The sky is sunny creating possible vapor like phenomenon
Wind speed	No wind (0 to 5 knots)	The gas accumulate faster at the same spot as no wind disperse it
	Calm wind (5 to 15 knots)	The gas might propagate on site
	Strong wind (from 30 to 100 knots)	The gas will either be dispersed directly or move fast
	Evolving from calm to strong	The wind evolve making prediction of the gas cloud evolution harder
Wind direction	From 180°	The wind direction propagate or not the gas cloud towards a work permit
	From 200°	The wind direction propagate or not the gas cloud towards a work permit
	From 220°	The wind direction propagate or not the gas cloud towards a work permit
	Moving from 180° to 220°	The wind evolve making prediction of the gas cloud evolution harder

Some specificities of those parameters must be explained in more details. First, the leak intensity is translated into a flowrate of gas exiting the process and is representative of the impact of the leak on the process. The smallest leaks have no impact on the process. Therefore, they are considered as having a leak intensity with a flowrate of 0kg/s. Then, the gas nature parameter was set as being CH₄ for every scenario as it is the gas that is the most commonly present on sites. More complicated weather conditions, like rain, were not implemented as the CCTV images could not be modified to fit these conditions. Finally, the wind characteristics are expressed using nautical units, as FPSO facilities are situated in deep waters. Therefore, the wind speed is in knots and the wind orientation is in degree from the north.

The scenario duration was defined at fifteen minutes per scenario based on recommendations from domain experts (see section III.2.2.2). This limitation eliminated the interest of the escalation of gas leak scenarios. Moreover, this limitation impacted the number of scenarios to be performed to limit the operator tiredness during tests.

Therefore, only five scenarios were defined following the new set of parameters and performed during the testing (see Table III-4):

- 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 to. It is expected that the operator will take measures to solve the leak but will not shut down the process.
- 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 request. It is expected that the operator will need to have more information to validate the fact that a leak is running in the process but will still order evacuation of the personnel working on site.
- The third scenario (repetitive acoustic detection without confirmation) represent the sensors defection with an alarm that comes and go being either a false alarm or a very low gas leak. It is expected that the operator will need more information to validate the fact that a leak is running in the process.
- The fourth scenario (high risk situation with multiple detections) is a high-risk scenario with multiple sensors detection and people with 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 the personnel 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 choice. It is expected that the operator will ask for personnel evacuation before the second alarm start.

Table III-4: Scenarios selected for user testing.

Scenario	Leak position	Leak intensity	Impacted Drager sensors	On-site permits	Maintenance	Weather	Wind
Scenario 1	Mezzanine deck HP separator top	2 000 kg/h	DRIR 2104	None	OK	Cloudy	7 kt constant from 202°
Scenario 2	Upper deck MP separator right side	0 kg/h	None	Cold/close	OK	Cloudy	From 15 kt to 30 kt, from 180° to 220°
Scenario 3	Upper deck between MP et LP separators	0 kg/h	Repetitive acoustic detection	None	OK	Cloudy	56 kt constant from 179°
Scenario 4	Process deck between separators	20 000 kg/h	DRIR 2003 then 2002 then 2004	Hot/close	Late ballon HP	Sunny	2 kt constant from 202°
Scenario 5	Upper deck MP separator right extremity	2 000 kg/h	Late DRIR 2202	Cold/far	OK	Sunny	From 15 kt to 65 kt, from 223°

The scenarios were performed following a similar process to allow result comparisons. The scenario process was defined using the BPMN format (see Figure III-14). During this process, a first phase of approximately 4 minutes is given for the operator to reach realistic working condition and not be waiting for the leak to be detected. Then the impact of the leak is reported on the process based on the values defined in the scenario. Then one minute after, the acoustic sensors are activated which start the alarm and reveal the detected leak. Then gas concentration sensors activate as well. Once the decision is made to act on the leak, the user is asked to call for the site manager (played by the wizard who run the experimentation as The Wizard of Oz principle) and to report his/her decision. Finally, the operator is asked to complete an experience feedback form and the scenario is considered as over.

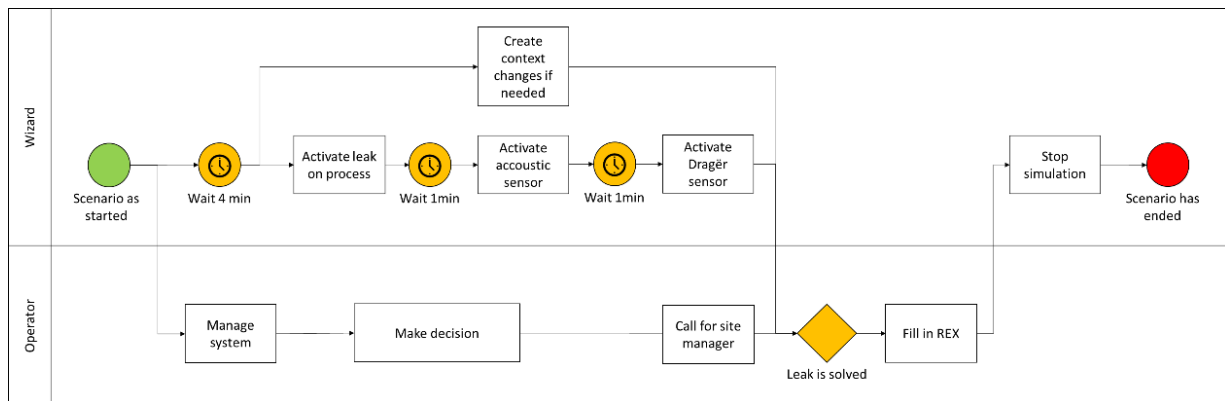


Figure III-14: BPMN model of every scenario.

During each scenario, user activity and usage of the prototype was recording using a camera (see part 2 section II.3.4.4) to be analyzed later. Due to the protocol predefined experimentation process, the recorded activity from each scenario will be comparable and lead to conclusion regarding the operator usages.

Experience feedback for anchor extraction

As defined in the scenario model (see Figure III-14), the last task proposed to the tester was to complete an experience feedback form. This task aimed at identifying the reality anchors used during the situation definition. Three different types of experienced

feedback forms were used to characterize reality anchors use (see part 2 section II.3.4.3).

The first feedback type is based on the existing operators' shift book which is currently used to transfer instructions at the end of a shift from an operator to his/her successor. This experience feedback form (see Figure III-15) is presented as a blank sheet to offer a free expression space to the operator to express his/her analysis of the situation without any clue about the expected information.

Shift book

Scenario: Date:

Operator:

Figure III-15: Example of shift book experience feedback form.

The second feedback (see Figure III-16) type is organized in three parts. The first part is titled "situation description". In this part, the operator is expected to describe the situation that happened during the scenario. The second part is titled "situation analysis". In this part, the operator is expected to explain what happened and what he understood of the situation. The third and last part is titled "actions taken". In this part, the operator is expected to write down the actions made and to justify them.

Experience feedback

Scenario: Date:

Operator:

Description of the situation:

Analysis of the situation:

Performed actions:

Figure III-16: Example directed experience feedback form.

The third feedback type (see Figure III-17) is organized as a questionnaire. It asks queries regarding elements of the situation. These queries are organized in three parts: (1) query regarding the perception of the situation, (2) query regarding the comprehension of the situation and (3) query regarding the projection of the situation.

Query-based experience feedback

Scenario: _____ Date: _____

Operator: _____

Description of the situation: _____

Leak position:	Leak intensity:
Wind direction:	Wind speed:
Number of permits on site:	Permit on site nature:

Figure III-17: Example of query-based experience feedback form.

As these experience feedback forms ask for increasingly detailed and oriented information regarding the situation, it has been decided to ask operators to gradually answer different forms. This means that shift book type forms are provided before the oriented form and that the oriented form itself is provided before the query type form. To collect every type of experience feedback form for every scenario, an order of scenario process and their corresponding feedback forms was defined (see Table III-5).

Table III-5: Scenario and experience feedback form process order

	<div style="display: flex; align-items: center; justify-content: center;"> Tests order → </div>				
	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

Following this scenario order ensured a full cycle for the scenario order and ensured two shift book type form and two directed type form for each scenario. As the query

type form is very descriptive and would bias the operator information memorization, it was chosen to only recover one of such form type for each scenario.

SA evaluation technique

As this study focuses on the impact of reality anchors availability on the user situation awareness, it was decided to evaluate the user situation awareness. This evaluation was performed using the Situation Awareness Rating Technique (SART).

The questionnaire used is the original form as defined by Taylor for the aeronautic military industry (Taylor 1990). As discussed previously (see part 2 section II.3.4.2), the SART is a subjective self-rating technique that focuses on nine constructs that have been evaluated as major elements for situation awareness rating.

As not every participant of the experimentation had the required English level outside the technical work vocabulary, French translations were provided.

III.2.4.2 Prototype implementation

Following the protocol definition, the prototype must be implemented. The goal is to implement every reality anchor defined in the previous steps into a digital twin prototype. As access to a working oil-and-gas functioning site was not a possibility, it was chosen to implement a simulation of digital twin. However, working with a simulation enabled as well to provide flexibility to the prototype implementation.

This prototype is called a simulation of a digital twin as it aims to represent a real-time decision-making support digital twin (see part 1 section I.4) but is not linked to a physical twin but simulate data as if it was coming from one. The use of a simulation created limitations as for the reality anchor representation in the prototype. Therefore, three reality anchors could not be implemented: (1) the Closed-Circuit Television (CCTV) images were replaced with static images of the site, (2) the Infra-Red (IR) images were not implemented and (3) the process Key Performance Indicators (KPI) trends could not be implemented neither. Apart from these three reality anchors, every other was implemented in the prototype.

The Wizard of Oz principle

The control room prototype was implemented using the "Wizard of Oz" paradigm (Dahlbäck, Jönsson, and Ahrenberg 1993). The "Wizard of Oz" paradigm proposes to use another human to control the behavior of the prototype and give the user the feeling that the prototype works by itself. This principle aims at providing complex behavior capabilities without implementing complex algorithms and flexibility to test multiple scenarios.

To reach these goals, the "Wizard of Oz" prototype was implemented as a two players video game. The first player, the wizard, on his side (see Figure III-18), can change every reality anchor value in the prototype to adapt to the scenario defined in the protocol.

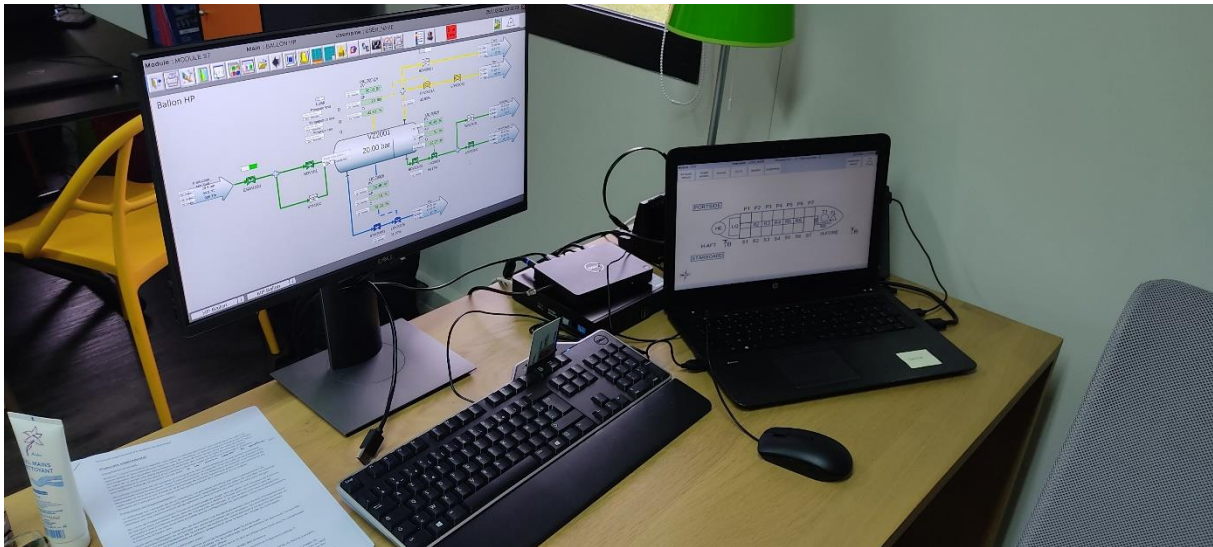


Figure III-18: First player experimentation set up.

The second player, on his side (see Figure III-19), see the updated information and can perform the needed tasks.

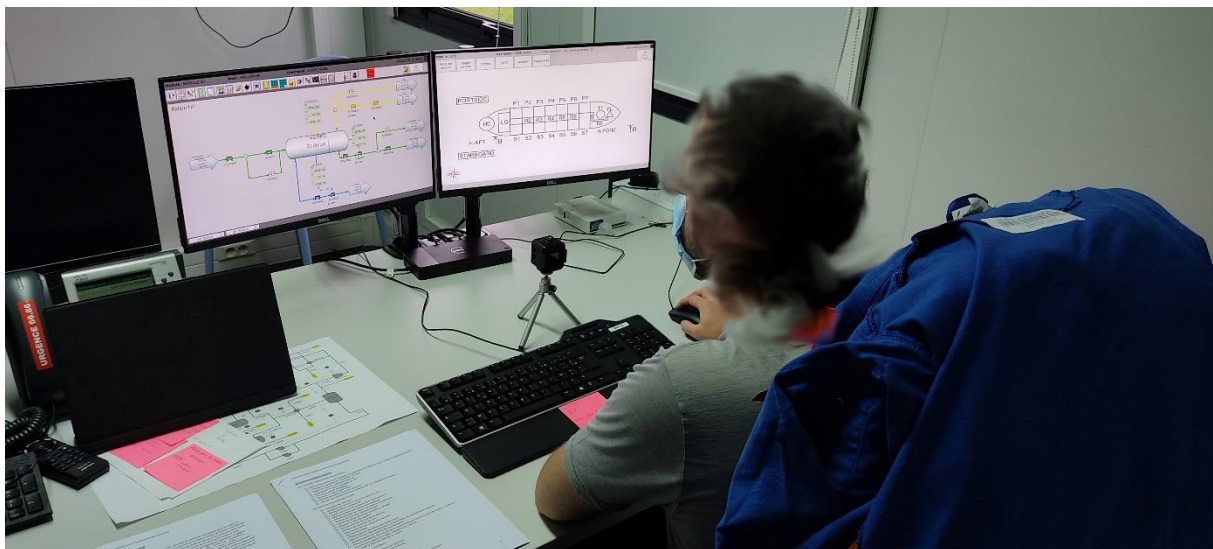


Figure III-19: Second player experimentation set up.

During the experimentation, the two players were separated in two rooms. The operator was located in a created control room to accentuate the realistic simulation aspect.

Interface form choices

This study aims at improving situation awareness based on data implemented in the SASS. Therefore, no study was conducted on the interface organization. However, to ensure that the implemented interface does not negatively impact user performance, the interface was designed based on UX design requirements and iterated with an oil-and-gas operator.

The company Yumaneed¹⁶, specialized in UX design counselling, performed an UX testing based on previous control room interface design to generate preliminary recommendations for future interface implementation. The recommendations were implemented in the interfaces.

The two interfaces resulting from this implementation are presented in the following section.

Process interface

The process related interface shows, as developed in section III.1.1, an oil-and-gas two stage separation process. The process is composed of two views respectively for a high-pressure HP separation stage (see Figure III-20) and a medium pressure MP separation stage (see Figure III-21).

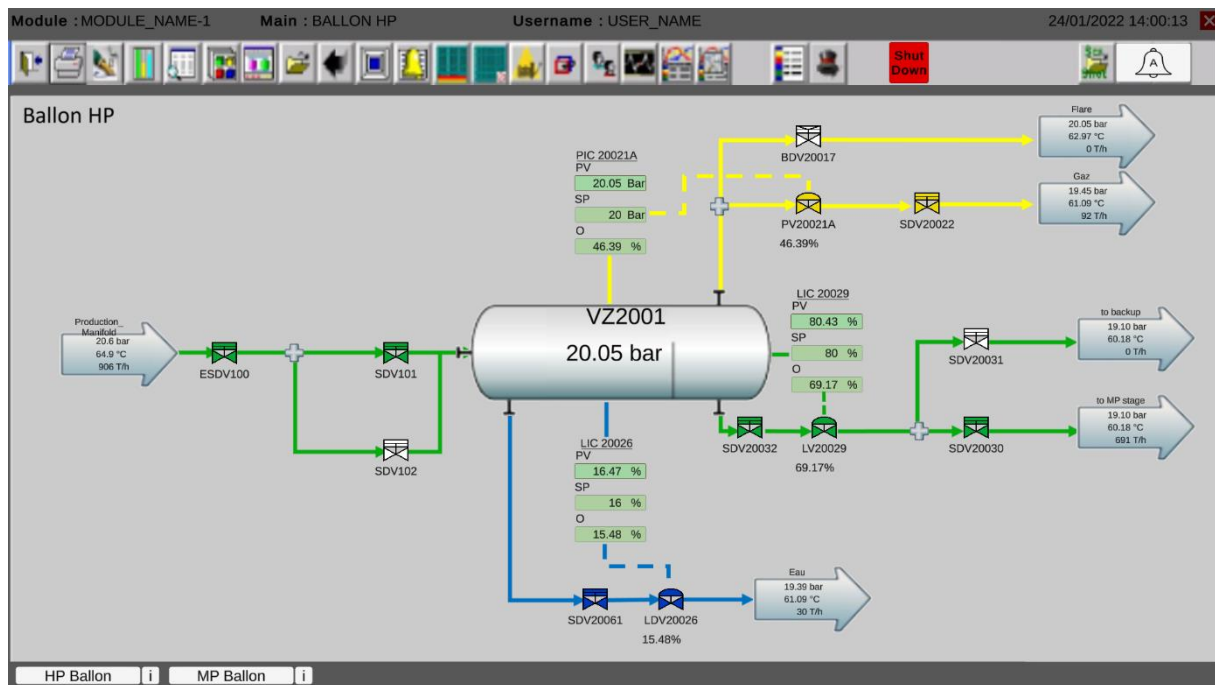


Figure III-20: High pressure stage interface.

The HP stage starts with an entry at 20.6 bar, 64.9°C and a flow of 906 t/h. These values are set based on a real stage currently performed on a real FPSO of the TotalEnergies company. Follow then a set of valves leading to the separator. Out of this separator, three types of fluids are separated, the water (in blue), the oil (in green) and the gas (in yellow). Each of these outputs are controlled by regulators and the associated valves to ensure specific set point are reached. A flare system is implemented on the gas output for emergency measures and the use of a back-up medium pressure stage is proposed for the oil output.

¹⁶ <https://www.yumaneed.com/> (consulted last 04/08/2022)

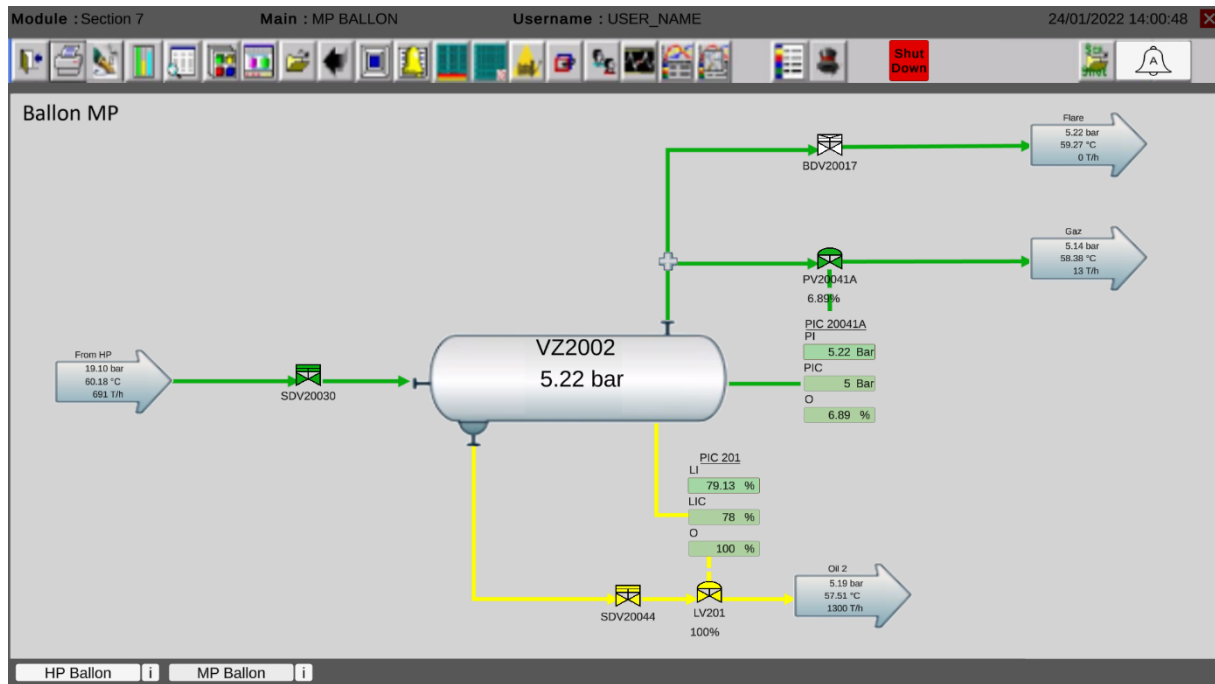


Figure III-21: Medium pressure stage interface.

The MP stage starts off at the oil output of the high-pressure stage. In this stage, the oil is re-separated to extract more gas. The medium pressure separator, in the center of the display, has two outputs. One output is for oil and water (in yellow here) and the other one is for the gas (in green here). Both outputs are controlled in pressure, for the gas, or in level, for the water and oil, to follow optimal values. As for the high-pressure stage, a safety line to the flare is also part of this stage.

Both interfaces are defined with general information like the section name, the type of separator observed, the username of the operator and the current date and time. Under, a screen shot of control room standard buttons that are not used by the operator in the presented context is showed to increase realism. As part of these buttons, two activable buttons have been replaced and are actionable: (1) the “Shut down button” enables the user to start the shutdown procedure for the observed separator and (2) the alarm button that blink and get red in case of an alarm. At the bottom of the screen, button enables the user to switch the process stage views.

Context interface

The context related interface shows four 2D views of the site to enable the operator to have a full image of the section where the process is performed. These four views give the operator context of where the managed equipment is and what events are happening on the site. The four views are (1) a longitudinal view of the section (see Figure III-22), (2) a view of the process deck (see Figure III-23), (3) a views of the mezzanine deck (see Figure III-24) and (4) a view of the upper process deck (see Figure

III-25). For prototyping simplicity and realism, the images used for the views are layouts of a FPSO of the TotalEnergies company that is used as model for the process part.

The longitudinal view (see Figure III-22) has been implemented for the operator to have a global view of the three levels of the section constituting of his process. On this view can appear context information such as the elevation of the position detected by acoustic sensors, the position of work permits or the orientation of the FPSO and the direction of the wind. However, no information is available on this view regarding the gas concentration level detection system. This information is available on the different deck views.

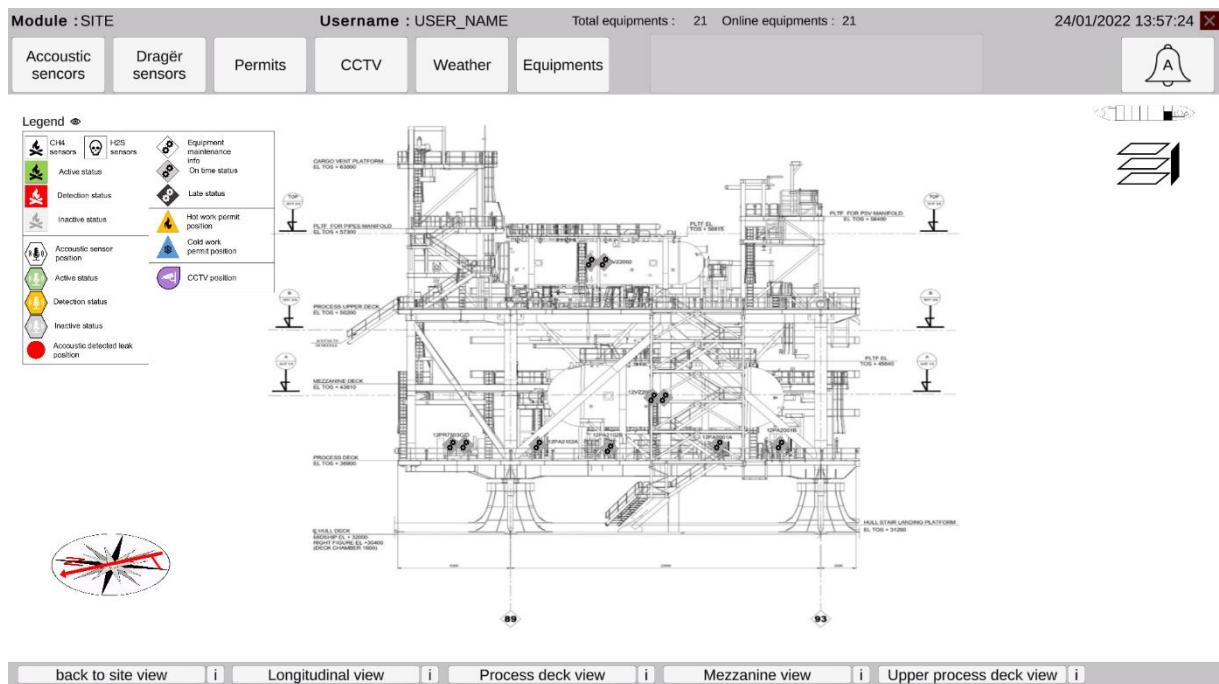


Figure III-22: Longitudinal view of the site.

The views of the process deck show multiple pieces of equipment that are not related to the process being managed by the operator. However, these pieces of equipment have been left on the to see how their presence influences the operator's decisions and for realism. This view of the process deck gives the operator a view of the high-pressure separator context. It shows the permit(s) in the area if any, and the position of the gas leak acoustic detection if this one is detected on this deck. In addition, it shows the position, type and status of the Dräger sensors (represented by the green icons). Overall, this view completes the information one of the previous one and focuses on the specifics of this deck.

Part III: Oil-and-gas use case: Gas leak on off-shore rig decision making

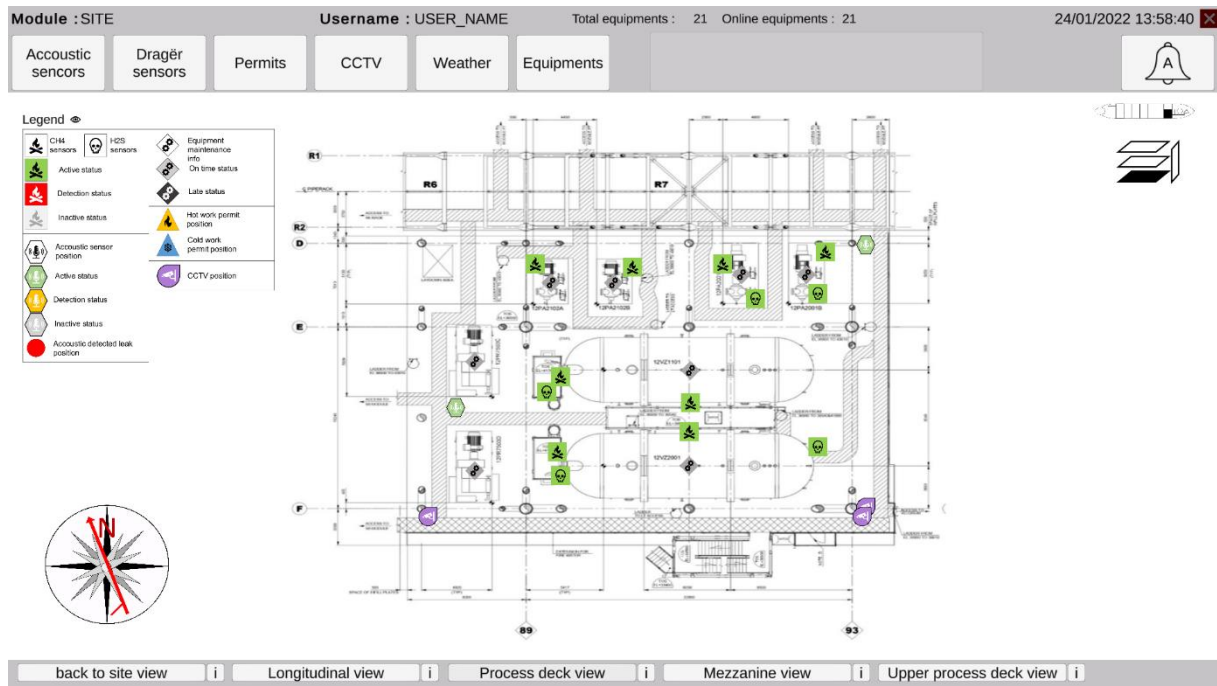


Figure III-23: Process deck view of the site.

The mezzanine deck gives access to the top of the high-pressure separator due to his size. This view has the same information than any deck views.

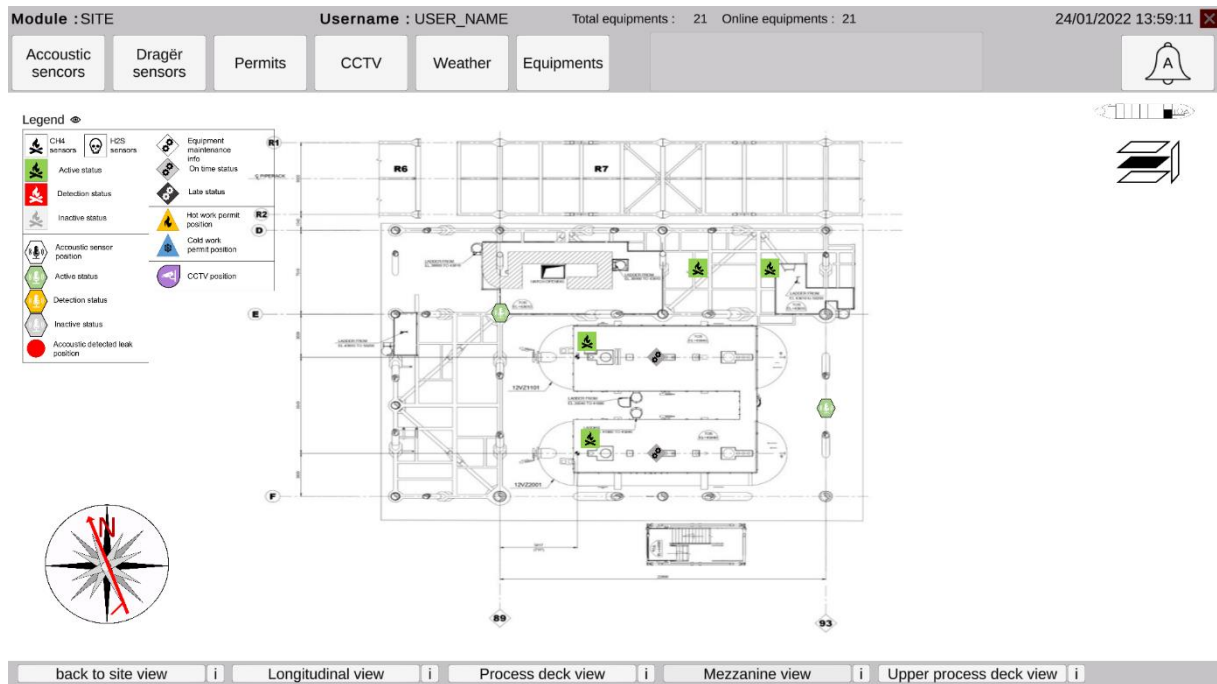


Figure III-24: Mezzanine view of the site.

The upper process deck has two separators and one is the medium-pressure separator introduced in the process stage. The information available on this view are of the same type as the one available in every other deck view but related to this deck.

Part III: Oil-and-gas use case: Decision Making in the Event of a Gas leak on an Offshore platform

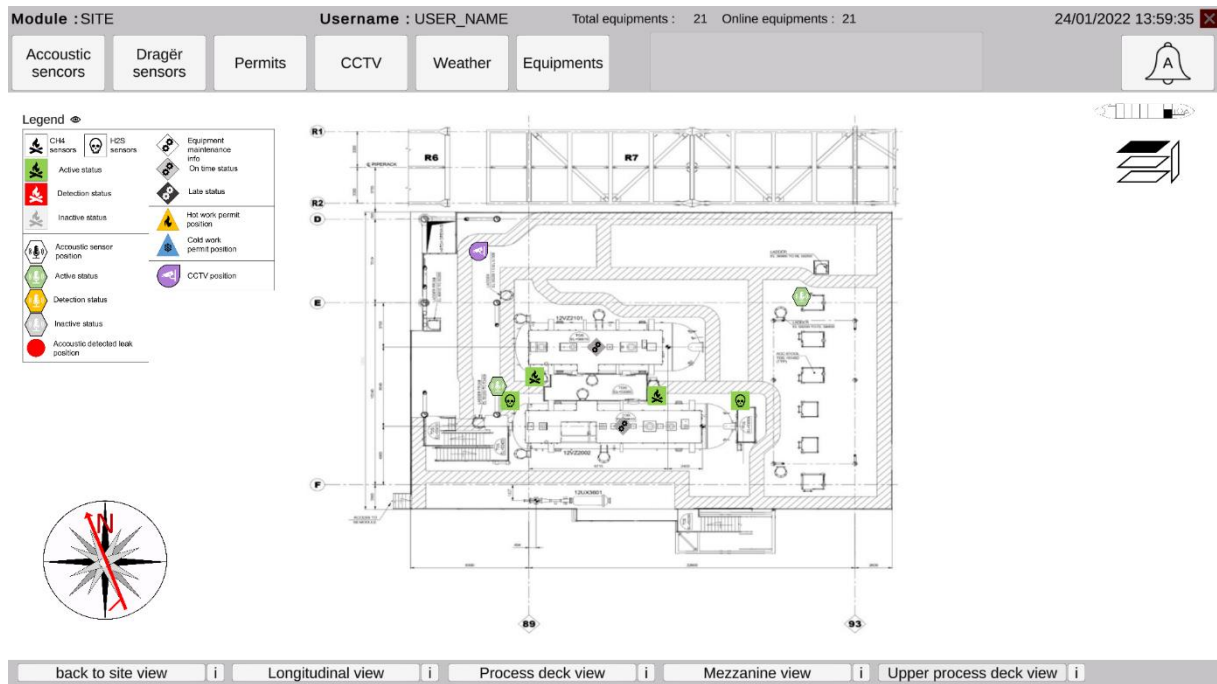


Figure III-25: Upper process deck view of the site.

As part of the site display interfaces, additional reality anchors related to the overall section are made available to the operator. The information is provided via separated windows. The information is related to six different categories:

- The acoustic sensors of the site (see Figure III-26). This window gives information on identification, deck position, type of sensors, and status (active, inactive or in detection).

Accoustic sensors	Dragër sensors	Permits	CCTV	Weather	Equipments
Accoustic sensors					Show <input checked="" type="checkbox"/>
ACC0001	Process deck	Accoustic	Active	■	
ACC0002	Process deck	Accoustic	Active	■	
ACC0101	Mezzanine deck	Accoustic	Active	■	
ACC0102	Mezzanine deck	Accoustic	Active	■	
ACC0201	Upper process deck	Accoustic	Active	■	
ACC0202	Upper process deck	Accoustic	Active	■	

Figure III-26: Information available related to acoustic sensors.

- The Dräger sensors of the site (see Figure III-27). This window gives a list of the Dräger sensors on the section of the site. In the same fashion as for the acoustic sensors, a list of the Dräger sensors presenting, their ID (identification name), position on the section, type and status is made available to the operator. Due to the number of sensors, this list can be scrolled to access every sensor.

Sensors ID	Position	Type	Status
DRIR1001	Process deck	H2S	Active ■
DRIR1002	Process deck	H2S	Active ■
DRIR1003	Process deck	H2S	Active ■
DRIR1004	Process deck	H2S	Active ■
DRIR1005	Process deck	H2S	Active ■
DRIR2001	Process deck	CH4	Active ■
DRIR2002	Process deck	CH4	Active ■
DRIR2003	Process deck	CH4	Active ■
DRIR2004	Process deck	CH4	Active ■
DRIR2005	Process deck	CH4	Active ■
DRIR2006	Process deck	CH4	Active ■
DRIR2007	Process deck	CH4	Active ■

Figure III-27: Information available related to Dräger sensors.

- The work permits currently validated on the site (see Figure III-28). This window displays all the validated work permits with their ID, the type of work (cold or hot), the impacted equipment, the number of operators intervening for the work and the date and hour of start and end of the work.

ID	Type	Equipement	Number of operator	Start	Finish
PS7C2026	Cold	Mezzanine deck ladder	3	06/07/2021 - 11:12	06/07/2021 - 17:00

Figure III-28: Information available related to permits on the section of the site.

- The images from the CCTV of the site (see Figure III-29). In this prototype no actual video footage of the site CCTV where available. The choice has been made to use screen capture from the site 3D visit tool to present the user with realistic images of the site.

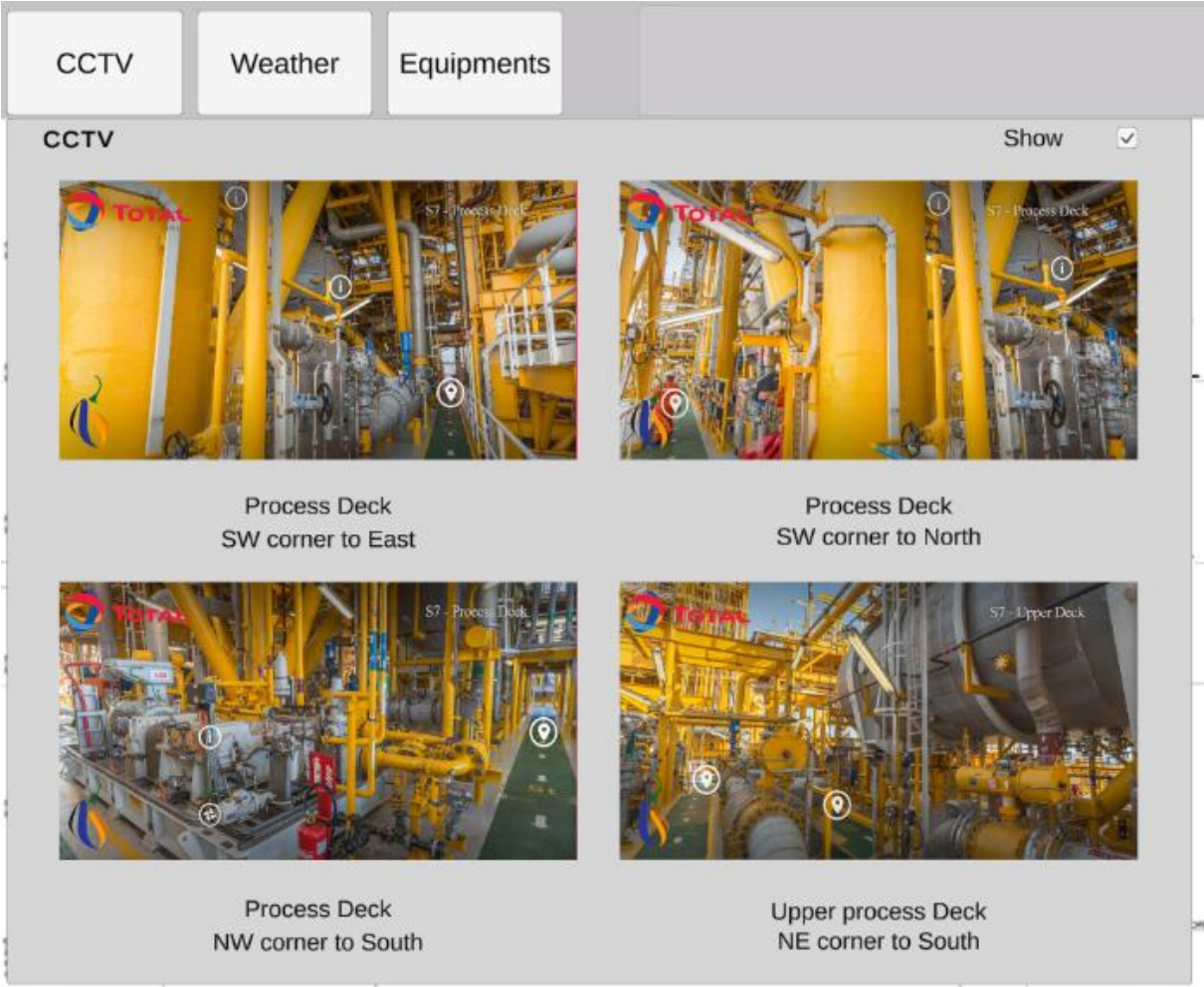


Figure III-29: Images available from the CCTV on the section S7 of the site.

- The weather (see Figure III-30). This window displays complete data information coming from the weather station of the site. Information extracted from the station are the wind speed, the wind origin (and therefore direction) the temperature, the humidity rate, the atmospheric pressure, and the cloudiness.

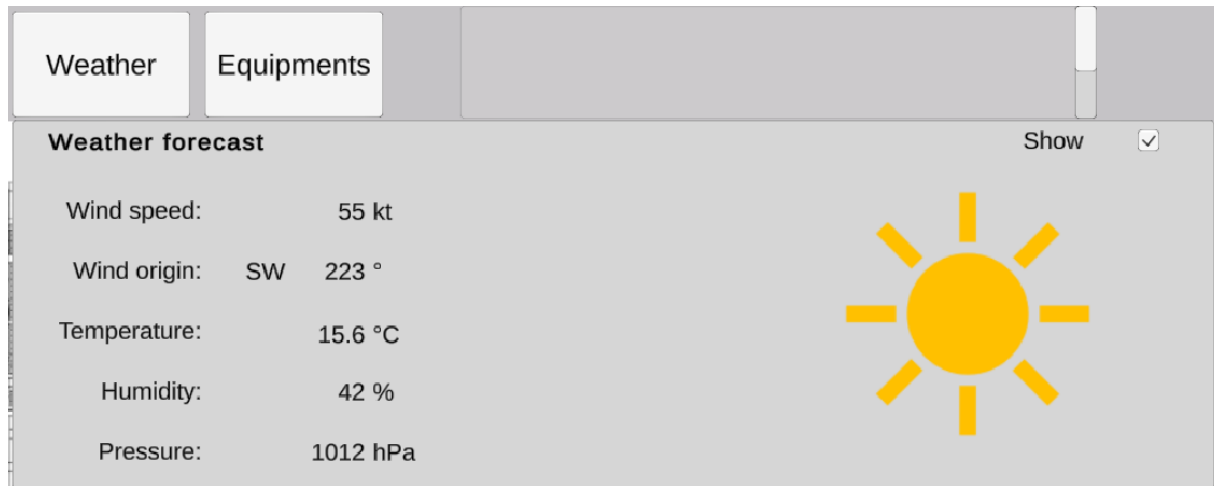


Figure III-30: Information available related to weather on site.

- The equipment on the section S7 of the site (see Figure III-31). This window displays the list of the equipments and the last and next date of preventive maintenance as well as the status of this maintenance (on time or late (not performed at the exact planned date)).

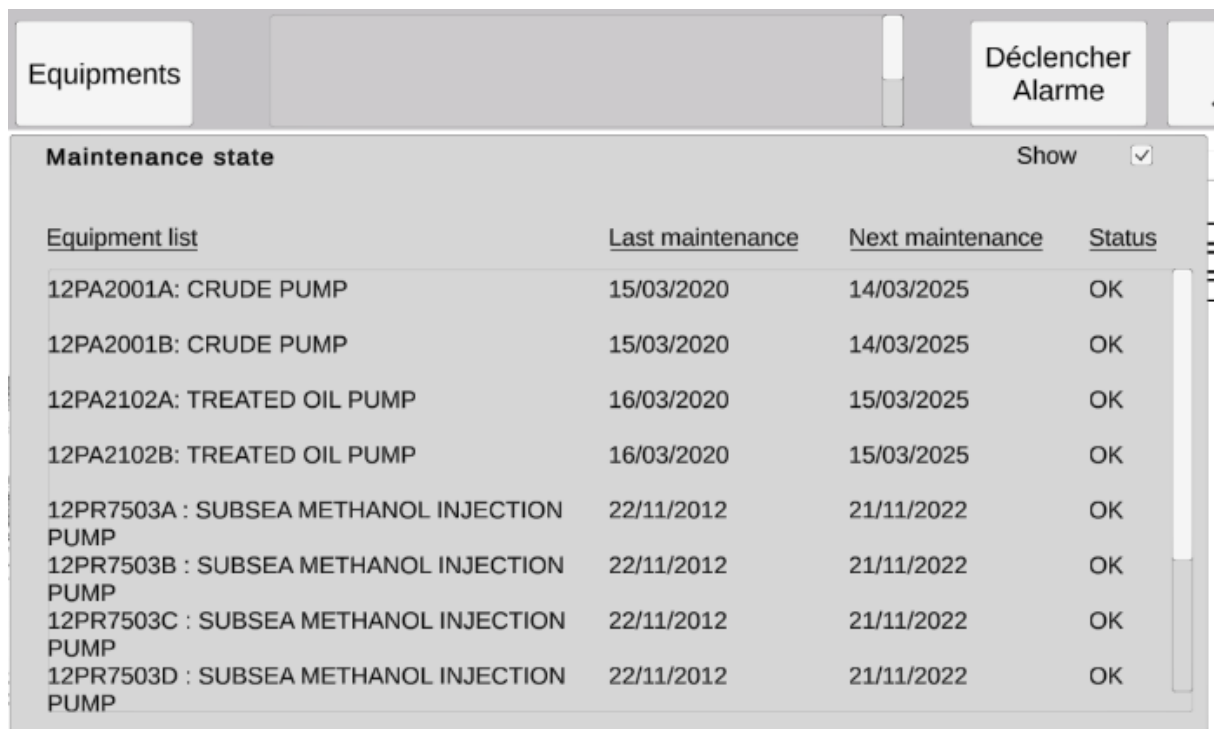


Figure III-31: Information available related to equipment on the section of the site.

In case of alarm, an alarm information space enables the user to access the alarm-related reality anchors (see Figure III-32 and Figure III-33). In the case of an acoustic detection, the available reality anchors are the type of detection, the time of the detection, the position of the leak detection, the flow rate of the leak and the estimated impact.


<u>Acoustic detection</u>	12:50	
Position:	Upper process deck	
Flow rate range:	0.1 à 1 kg/s	
Impact:	Medium injury	

Figure III-32: Acoustic detection information example.

In the case of gas concentration detection, the reality anchors available are the type of detection, the time of the detection, the name of the sensor that have detected an anomaly, the position of the sensor and the type of gas that have been detected.


<u>Dragër detection</u>	12:50	
Sensor:	DRIR 2001	
Position:	Process Deck	
Type:	CH4	

Figure III-33: Gas concentration detection information example.

Implementation software

The need for the prototype to be controllable from both the user and the Wizard of Oz inspired the direction of the implementation to be performed in the form of a two-player video game. To implement such game, the unity platform¹⁷ was chosen. This development tool was chosen for different reasons:

- The platform is free access for educational purposes.
- Its multiples online tutorials made it a great base to learn on.
- A module for online video game implementation were already created (called Mirror) and shared by the community which made the two-player configuration easier to implement.
- The platform is fully capable to deal with 3D models or even virtual/augmented reality if it was to be used in the future.

The unity software is using a proprietary graphical interface to enable world creation and C# files to define entities algorithms.

The version used for the implementation of this prototype is Unity 2019.4.17f1.

The designing interface is separated in 5 main areas (see Figure III-34):

- 1) The Scene area is the main area of the entity design. It is in this area that the implementation of the graphical interface is designed.
- 2) The hierarchical entity tree is the area where all the entities and their parent/children relationships are defined. The entities present in this hierarchy can be specific to the scene or can be predefined (called prefabs).

¹⁷ <https://unity.com/> (accessed last 04/08/2022)

- 3) The inspector area is the description of the entity parameters. These parameters are defined by scripts. These scripts can be predefined, like the "Rect Transform" script that defines the position of the graphical part of the entity in the scene, or defined by the designer.
- 4) The "alarm process" script is a designer defined script that describes the behavior of the entity.
- 5) The project area displays the hierarchy of the files constituting of the complete project. This area enables to access and manage the C# files used to define the behavior of the entities or the predefined entities called prefabs.

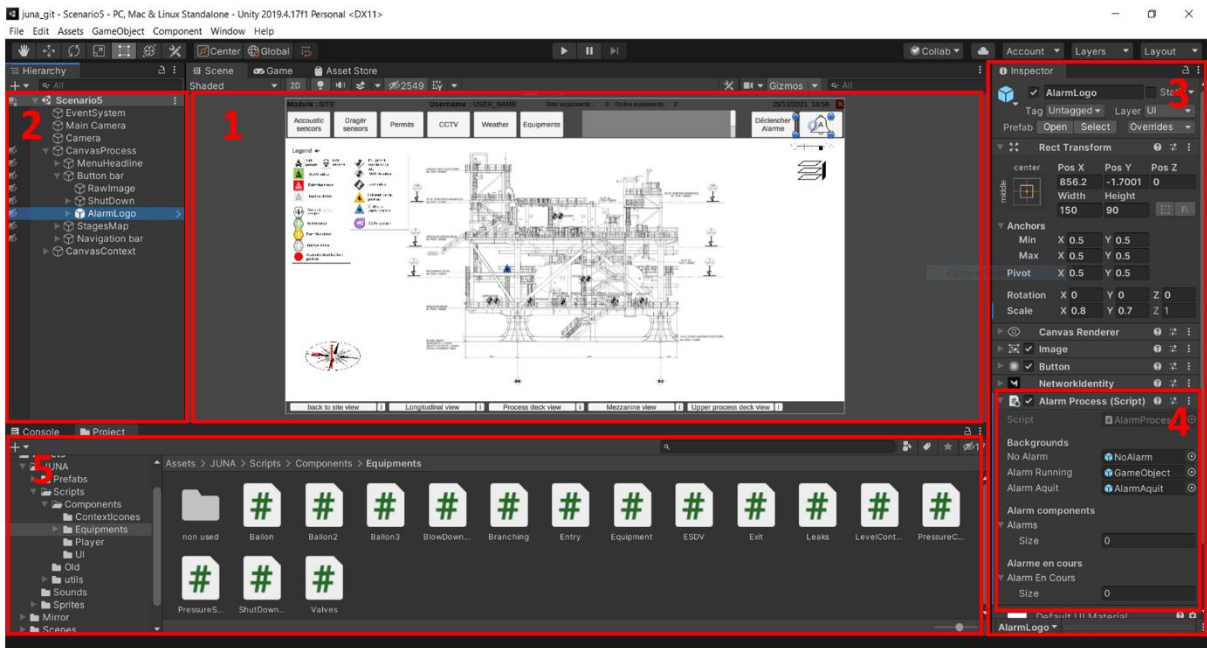


Figure III-34: Unity software interface organization.

The structure of the prototype is explained in the next section.

Prototype structure

The prototype implementation process was organized through a branch structure using the GIT hub solution. First, the project structure used to manage the different file types and their interactions with one another will be presented. Then, the scene structure used to ensure a functioning of the interface will be described.

Project structure

The project is organized in three main folders. (1) The prefabs, predefined interface entities, (2) the scripts, the files used to program interface behaviors and (3) the sprites, the images used to form the interface.

The prefabs are organized in four categories:

- The equipment are prefabs (predefined entities that act as guidelines for future entities creation) that defines the equipment of an oil and gas process. This includes separators, valves entry, exits and a valve control component.
- The map elements are the elements that appears on the site map to present elements of the situation. This includes the acoustic detection position, the sensors, the permits, the CCTV and the maintenance related information.
- The players are used to simulate the connection of two players to the game but does not have a physical presence on the interface.
- The UI related elements represent the prefabs used to shape the form of the entire interface. This includes the different used buttons, the site map, the process map, and different specific interactive entities that are linked to on-line functionality and enables the communication between the two players.

The scripts are organized in two main folders:

- The components folder regroups files related to equipment behavior to simulate the oil-and-gas process, the map icons behaviors, the player internal network behavior and the general user interface.
- The utils folder regroups files linked to the general behavior of the application and the network communication. It is mostly used to store files that defines class structures and data types.

The Sprites are organized regarding they type would it be CCTV images, equipment icons, map icons, the maps themselves of the weather logos.

In addition to these folders, the Mirror folder placed in the project contains the entirety of the Mirror module code.

This complete project structure enables to manage the large collection of files used in this project.

Scene structure

The scene system is the same for every scenario to ensure an identical interface experience. To create a new scenario the designer only needs to copy paste the structure and to change the specificities of the scene elements to adapt and create a new scenario without changing the interface performances.

A scene is composed of three mains components that are the cameras, a canvas for the process interface and a canvas for the context interface.

The cameras represent the view of the players. The use of these elements enables to create a two-screen display structure needed for the two interfaces structure expressed in the digital twin definition.

The canvas for the process is organized in four sub-categories:

1. The menu headline that contains general information such as the module name, the process being viewed, the username, the current time and the button for closing the screen.
2. The main button bar that contains images of general buttons not used in the experimentations but that serves to provide realistic interface that is like the one used in control room. It also contains the alarm button that is used to acquit alarms.
3. The process maps that contain the two process maps used in the experimentation. Each equipment that composes the process is organized in these maps elements to form the part of the process.
4. The navigation bar is composed of the button that enables to switch from one process map to another.

The canvas for the context is organized in four similar sub-categories:

1. The menu headline that contains general information like the module name, the username, the total number of equipment, the number of equipment online, the current time and the close screen button.
2. The context maps that contain five views of the site, the keys and a button that return to the general site view. Each view of the site is organized in the same fashion with the map element that contains every icon and the map image, the logo that shows which map is on and the wind rose.
3. The menu button bar that contains the buttons that provides the complementary information on the situation as well as the alarm information and the alarm acquit button.
4. The navigation bar is composed of the button that enables to switch from one site view to another.

This structure makes the prototype scenarios flexible and enables the reuse of the prototype for further testing if needed.

III.2.5 Results analysis

To collect results from the testers, the protocol defined previously (see section III.2.4.1) was used with the implemented prototype (see section III.2.4.2). Three sources of results are looked into from the tests:

- The SART results provide insight into the effect of the prototype on the user SA through the DT ability to provide access to the element of the reality for each scenario.
- The experience feedback results enable to identify the reality anchors used by operators to describe a situation from different level of details.
- The activity analysis allows to identify the process used by operators to access information in the tool when confronted to the necessity to assess a situation.

Those three sources of results are presented in the following sections.

III.2.5.1 SART results analysis

To enable analysis and comparisons, the results of the SART have been implemented into radar charts to enable comprehensive evaluation (W.A.N.G. et al. 2017). These figures are presenting the operators ratings on regards to a specific scenario.

First scenario: low risk situation with detection confirmation

First scenario presents a situation of acoustic and gas concentration detection of a supposed medium size gas leak on the mezzanine deck. In this scenario, no permit is currently being performed on the site and the weather is cloudy with a constant 7 knots wind.

This scenario was expected to show the following result:

- Mediumly instable as the size of the leak could evolve,
- Mostly simple as multiple alarms facilitate the validation of the presence of a leak,
- Mediumly variable as half of the information related to situation variables does evolve in the situation,
- Mediumly arousing as the situation is usual for them,
- The concentration of attention should be medium as well as the operator should be able to keep attention of the overall process and manage the situation at the same time,
- The division of attention should follow the same model,
- The spare mental capacity should be high to show the ability of the prototype to no overload the use,
- The information quantity should be high or medium (depending if the operator considers the maximum as if every information is available or if there is more information than needed) as every important information have been available to the user,
- The familiarity with the situation should be high as the scenario have been defined to be familiar to the operator.

Looking at the first scenario SART results (see Figure III-35), the results showed:

- Instability of the situation is mostly rated low with exception of operator 2.
- Complexity of the situation is mostly rated low with exception of operator 2.
- Variability of the situation is mostly rated low with exception of operator 2.
- Arousal is rated at different values with no found link between the evaluation.
- Concentration of attention is almost evaluated to the max by every operator.
- Division of attention is almost evaluated to the max by every operator.
- Spare mental capacity ratings are scattered in the higher values.
- Information quantity ratings are scattered in the middle values.

- Familiarity with the situation ratings are mostly rated at the higher values with exception to operator 3 with the middle rating and operator 1 with the lowest rating.

A link in the rating of attention both in concentration and division on the attention can be seen. Every user kept its attention divided between multiple elements of the situation.

Moreover, at the exception of one participant, most participant agreed that the situation is not complex and do not have a great variability. These results correspond to the results expected for this first scenario, defined as a baseline for future situations.

Finally, the rating on the information quantity is set at the middle of the range. This rating can be considered as showing that enough information has been shared by the prototype. This result was expected, as the first scenario aimed at providing sufficient information for decision making without overcharging the user.

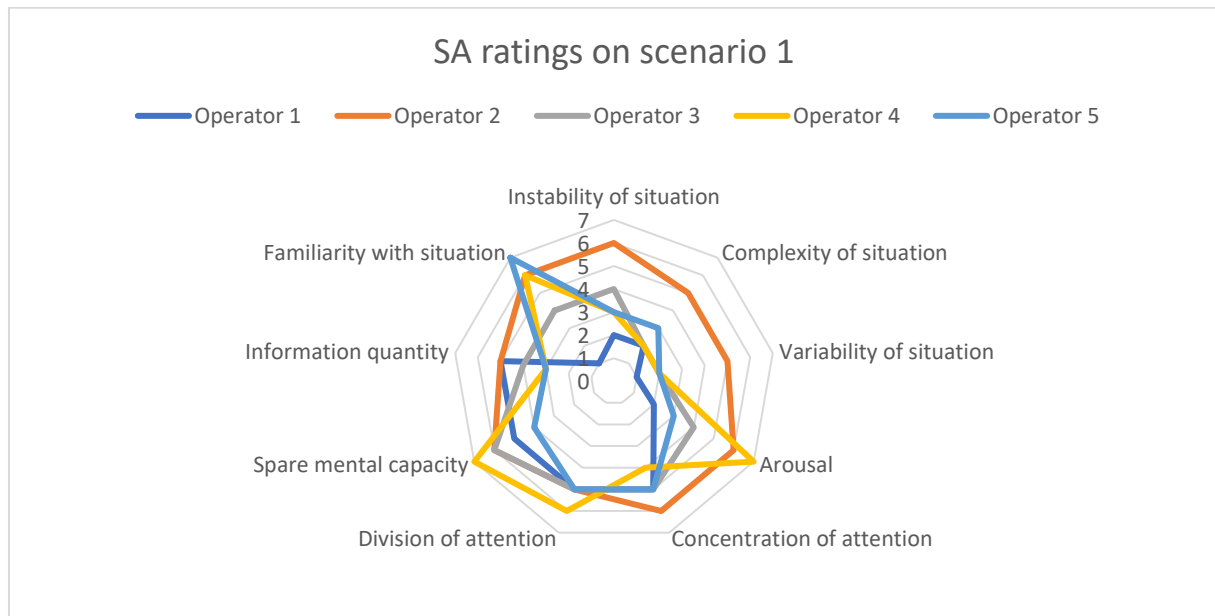


Figure III-35: SA ratings of the 5 operators on scenario 1.

Second scenario: low risk situation without confirmation from multiple sensors

Second scenario presents a situation of acoustic detection, from two sensors of a small gas leak on the upper process deck. In this scenario a cold work permit has been delivered for a work to be performed on the same deck and the weather is cloudy with a medium variable wind. The aim of the scenario is to bring uncertainty in the detection, to encourage users to validate their situation awareness using the tool and looking for additional information.

This scenario was expected to show the following result:

- Mediumly instable as there is no certainty of a leak being present,
- Mediumly complex as there is no certainty of a leak being present,
- Highly variable as most of the information related to situation variables does evolve in the situation and the certainty of leak is not present,
- Highly arousing as the gas leak is not confirmed,
- The concentration of attention should be medium or high as well as the operator should be able to keep attention of the overall process and manage the situation at the same time,
- The division of attention should be medium as the prototype is supposed to enable the user to keep track of the process and manage the leak situation,
- The spare mental capacity should be high or medium because of the search for the confirmation of leak,
- The information quantity should be medium or low (depending if the operator considers the maximum as if every information is available or if there is more information than needed) as no information have been made available to the user to confirm the gas leak presence,
- The familiarity with the situation should be high as the scenario have been defined to be familiar to the operator.

Looking at the second scenario (see Figure III-36), the results showed:

- Instability of the situation ratings are scattered in the low values.
- Complexity of the situation is mostly rated low.
- Variability of the situation is mostly rated low.
- Arousal ratings are mostly rated at the higher values with exception to operator 5 with the middle rating and operator 1 with the lowest rating.
- Concentration of attention ratings are scattered across the value range with three operators according with a rating of 5.
- Division of attention ratings are scattered across the value range with three operators according with a rating of 5.
- Spare mental capacity ratings are scattered in the higher values.
- Information quantity ratings are scattered across the value range.
- Familiarity with the situation ratings are mostly rated at the higher values with exception to operator 3 with the middle rating and operator 1 with the lowest rating.

Looking at the SART results, the ratings show more differences between each user than on the first scenario. This might be due to the uncertainty of the presence of a gas leak in this situation as some had doubts regarding validity of the detection.

On this scenario, the instability, complexity, and variability of the situation has been evaluated to a lower level by most users. This result diverges from what was expected.

This divergence can be explained by saying that the user doesn't consider the detection as valid and that therefore the situation is simple, stable and with few variables.

On the contrary, the level of arousal is evaluated higher by the operators. This result can translate the questioning from the user as to what the situation really is.

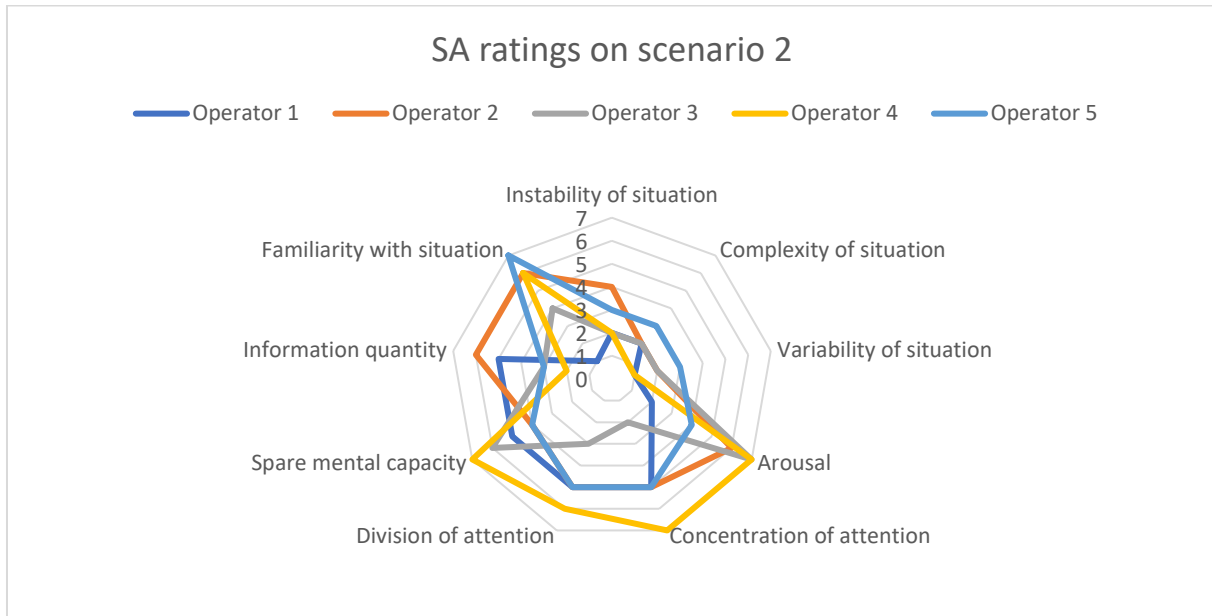


Figure III-36: SA ratings of the 5 operators on scenario 2.

Third scenario: repetitive acoustic detection without confirmation

Third scenario presents a situation of repetitive acoustic detection of a very small gas leak on the upper process deck. In this situation no work permit has been delivered and the weather is cloudy with a high-speed wind. The aim was to create another type of uncertainty. This uncertainty takes the form of the alarm activating and deactivating itself repetitively.

This scenario was expected to show the following result:

- Mediumly instable as there is no certainty of a leak being present,
- Mediumly complex as there is no certainty of a leak being present,
- Highly variable as most of the information related to situation variables does evolve in the situation and the certainty of leak is not present,
- Highly arousing as the gas leak is not confirmed and the alarm is repeating itself,
- The concentration of attention should be medium or high as well as the operator should be able to keep attention of the overall process and manage the situation at the same time,
- The division of attention should be medium as the prototype is supposed to enable the user to keep track of the process and manage the leak situation,
- The spare mental capacity should be high or medium because of the search for the confirmation of leak,

- The information quantity should be medium or low (depending if the operator considers the maximum as if every information is available or if more information than needed are) as no information have been made available to the user to confirm the gas leak presence,
- The familiarity with the situation should be high as the scenario have been defined to be familiar to the operator.

Looking at the third scenario (see Figure III-37), the results showed:

- Instability of the situation ratings are scattered in the low values with exception of operator 2.
- Complexity of the situation is mostly rated low.
- Variability of the situation is mostly rated low.
- Arousal ratings are scattered across the value range.
- Concentration of attention ratings are mostly rated in the medium value range with exception of operator 4 that rated it at the maximum.
- Division of attention ratings are mostly rated in the medium value range with exception of operator 4 that rated it at the maximum.
- Spare mental capacity ratings are scattered in the higher values with exception of operator 5.
- Information quantity ratings are scattered across the value range.
- Familiarity with the situation ratings are mostly rated at the higher values with exception to operator 1 with the lowest rating.

Most ratings are scattered across the value range which can be due to the uncertainty created in the scenario. One exception remains in the rating of complexity and the familiarity.

The scenario being voluntarily without validation phenomenon, the complexity of the situation complexity being evaluated low is unexpected.

This scenario, like others, was defined based on results from the interviews. Therefore, it is logical that most operators recognize the situation and evaluate it as very familiar. The exception of this analysis is for operator 1. However, looking at the familiarity ratings of operator 1 on every scenario and after looking at the feedback from the post test interviews, it can be said that its evaluation is different because he is not used to work with acoustic sensors and less confident with this technology.

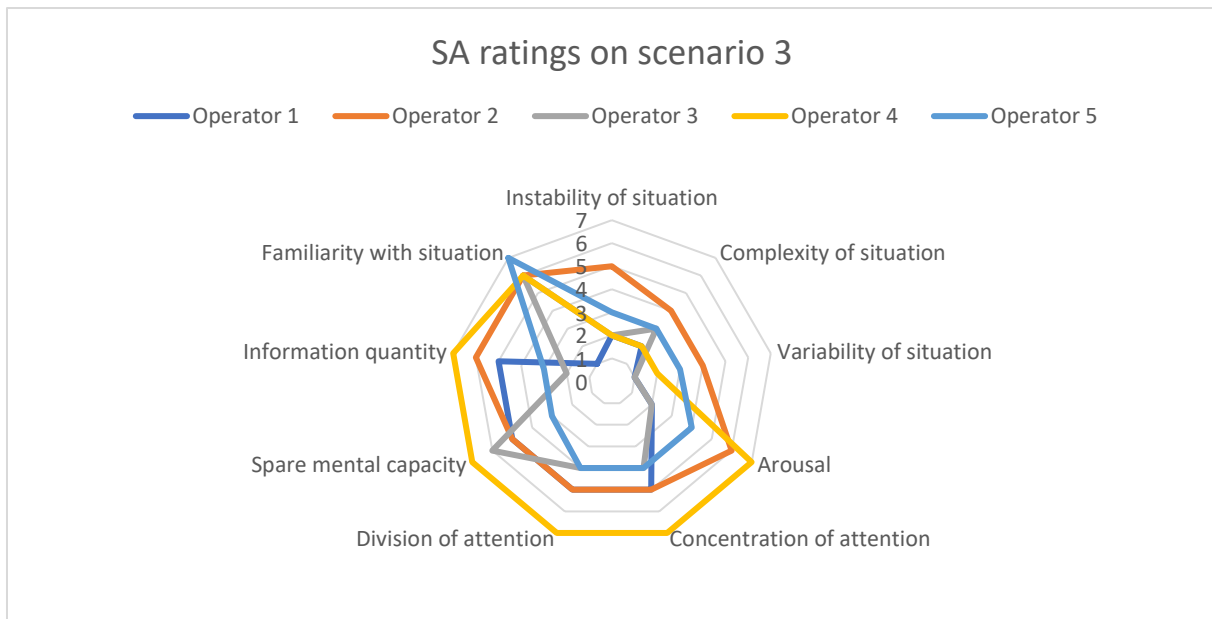


Figure III-37: SA ratings of the 5 operators on scenario 3.

Fourth scenario: high risk situation with multiple detections

Fourth scenario presents a situation of acoustic and multiple gas concentration sensor detection of a large gas leak on the process deck. In this scenario a hot work permit has been delivered and is performed close to the detection point. Moreover, the maintenance of the surrounding equipment is late and the weather is sunny with no wind. The aim is to create a situation that can have a critical impact and that evolve quickly toward a hazard.

This scenario was expected to show the following result:

- Highly instable as the situation is evolving rapidly,
- Simple as the number of alarms and the associated high risks make the decision simple,
- Highly variable as most of the information related to situation variables does evolve in the situation,
- Highly arousing as the risk involved is high and multiple alarms are involved,
- The concentration of attention should be high as the risks involved are high,
- The division of attention should be low as the decision should involve a direct evacuation and shut down solution and the attention must be then given in performing these tasks,
- The spare mental capacity should be medium because the solution should take most of the capacity,
- The information quantity should be medium or high (depending on if the operator considers the maximum to mean that every information is available) as every information have been made available to the user to confirm the gas leak presence,

- The familiarity with the situation should be high as the scenario have been defined to be familiar to the operator.

Looking at the fourth scenario (see Figure III-38), the results showed:

- Instability of the situation ratings are mostly rated in the highest values with exception of operator 1.
- Complexity of the situation ratings are mostly rated in the highest values with exception of operator 1.
- Variability of the situation ratings are mostly rated in the highest values with exception of operator 1.
- Arousal ratings are mostly rated in the highest values.
- Concentration of attention ratings are all rated in the highest value.
- Division of attention ratings are all rated in the high value.
- Spare mental capacity ratings are all rated in the high value.
- Information quantity ratings are all rated in the high value range (5) with exception of operator 2 that rated it at the maximum.
- Familiarity with the situation ratings are mostly rated at the higher values with exception to operator 1 with the lowest rating.

Looking at the results of the SART, apart from one operator, results are coherent with one another.

The instability, complexity and variability of the situation has been evaluated by high ratings. The arousal rating by the operators is evaluated high as well, this can be explained as its arousal is triggered by the high level of attention required to interact with the multiples factors involve in this scenario. However, the spare mental capacity is judged as sufficient with most ratings at 5 on 7.

The apparition of the awaited phenomenon with the implementation of the scenario shows the ability for the digital twin prototype to provide situation awareness to the user and to affect its evaluation of the situation as well as its personal cognitive phenomenon.

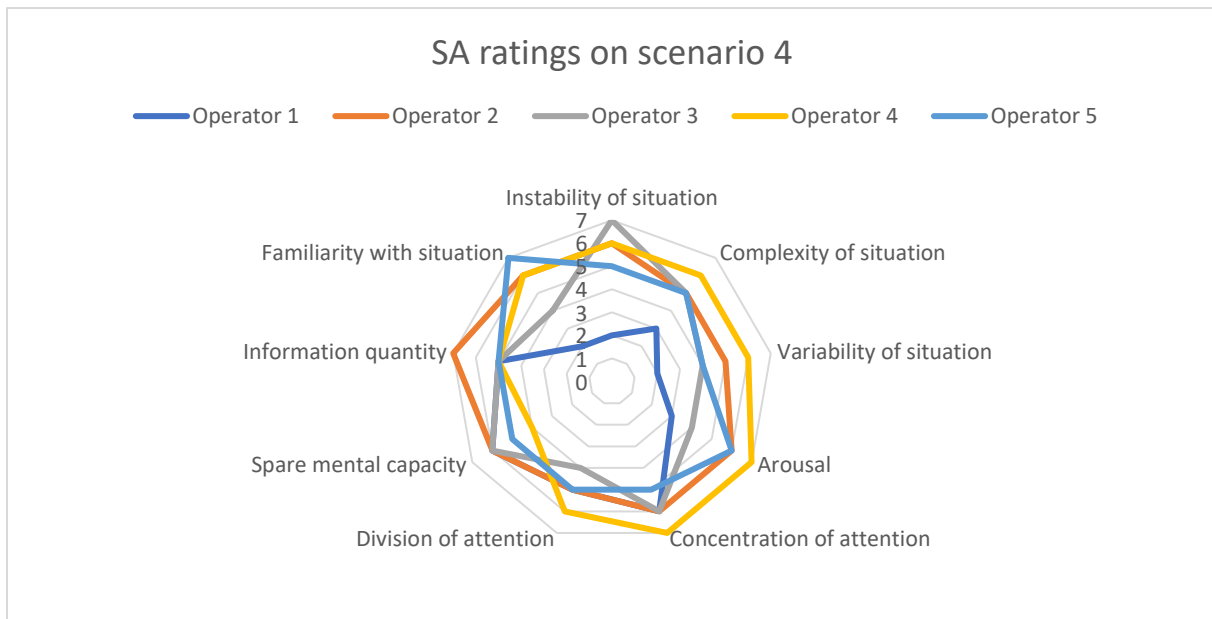


Figure III-38: SA ratings of the 5 operators on scenario 4.

Fifth scenario: medium risk situation with late confirmation

Fifth and last scenario presents a situation of acoustic detection followed by concentration sensor detection of a medium gas leak on the upper process deck. In this situation a cold work permit has been delivered and is performed on the deck below the point of detection. Moreover, the weather is sunny with a medium speed variable wind. This scenario aimed at providing detection confirmation (second alarm by second technology) later than in the first scenario with the addition of a work permit in the vicinity.

This scenario was expected to show the following result:

- Mediumly instable as the size of the leak could evolve,
- Mostly simple as multiple alarms and technologies facilitate the validation of the presence of a leak,
- Mediumly variable as half of the information related to situation variables does evolve in the situation,
- Mediumly or highly arousing as the situation is evolving later than anticipated with personnel at risk,
- The concentration of attention should be medium as well as the operator should be able to keep attention of the overall process and manage the situation at the same time,
- The division of attention should follow the same model,
- The spare mental capacity should be high to show the ability of the prototype to no overload the user,

- The information quantity should be high or medium (depending on if the operator considers the maximum to mean that every information is available) as every important information have been considered to be available to the user,
- The familiarity with the situation should be high as the scenario have been defined to be familiar to the operator.

Looking at the ratings (see Figure III-39), the results showed:

- Instability of the situation is scattered in the middle range of the value.
- Complexity of the situation is mostly rated medium.
- Variability of the situation is mostly rated medium.
- Arousal ratings are scattered in the medium and high values.
- Concentration of attention is mostly rated high.
- Division of attention are scattered in the medium and high values.
- Spare mental capacity ratings are in the higher values.
- Information quantity ratings are scattered across the value range.
- Familiarity with the situation ratings are mostly rated at the higher values with exception to operator 3 with the middle rating and operator 1 with the lowest rating.

The situation is evaluated as moderately complex and variable. This rating is probably due to the presence of a work permit in the vicinity. According to the ratings, the attention keeps being shared across the scenario and no lack of mental capacity is discernable. However, the evaluation of the information quantity is variable and no conclusion can be extracted on those values.

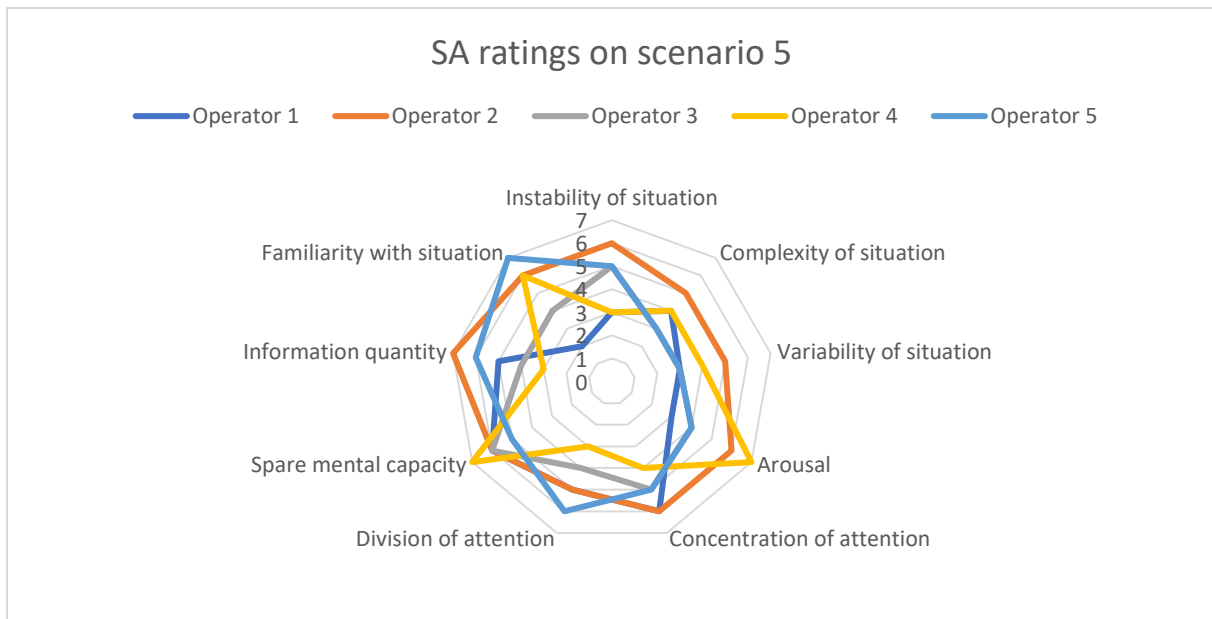


Figure III-39: SA ratings of the 5 operators on scenario 5.

Synthesis

In conclusion, among the scenarios, it can be said that:

- The operators are keeping a constant share of attention across the information. Supporting this ability is therefore important.
- The familiarity with the situation 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 acoustic sensors and the use of a new operational site brought operators to lower their rating in this category. It shows the importance for operators to be familiar with the site configuration and not only the developing situation.
- Regarding information quantity and spare mental capacity, usual information can be used to support operators while avoiding mental overload. This validate the fact that the tool can be used in 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 rating regarding instability, complexity and variability appears while having to deal with a fast-evolving risky situation involving humans.

III.2.5.2 Experience feedback analysis

As exposed previously (see part 2 section II.3.4.3), the experience feedback from the operators is gathered in three different forms:

- A free experience feedback form,
- A directed experience feedback form,
- A query-based experience feedback form.

To analyze the results from the experience feedback forms filled by the operator, a cartography of the reality anchors and the concept surrounding a gas leak situation have been defined in Table III-6

Table III-6: Concepts associated to the gas leak.

Main concepts	Sub-concepts
Gas leak	Leakage position
	Severity of the leak
	Confidence in the leak validity
	Direction of the leak
	Nature of the gas leak
	Flowrate value
	Date and time
	Cloud
Sensors	Sensors name
	Sensor types
	Sensor position
	Sensor status
Alarms	Number of alarms
	Alarm stability
Process	Equipment
Weather	Wind direction
	Wind speed
Permits	Number of people
	Permit date
	Permit name
	Permit position
	Nature of the permit
Others	CCTV
	Acoustic sensors
	Draeger sensors
	Pressure sensor
	Pressure in the process
	People in the vicinity
	Maintenance
	Level
	Hole dimension

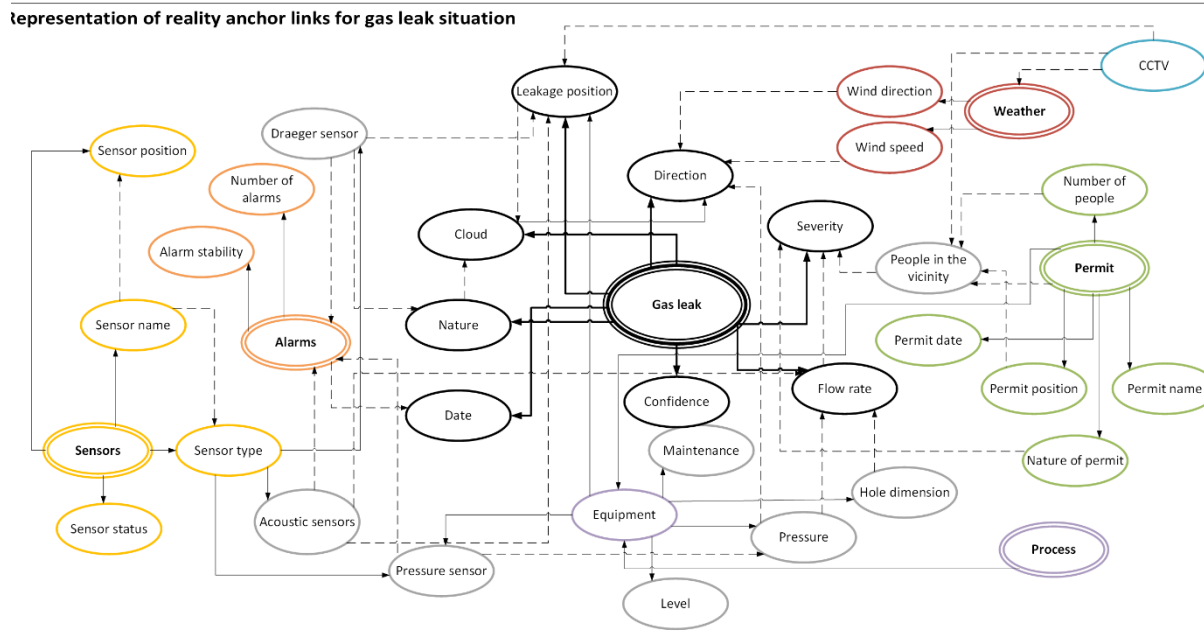


Figure III-40: Representation of reality anchors links for a gas leak situation.

Those main concepts are described using sub-concepts that are the reality anchors used by operators to acquire the situation awareness. Those sub-concepts are represented through a full arrow from the main concept in Figure III-40. For example, a sensor has a sensor type that can be acoustic, Dräger or pressure.

Some sub-concepts are carrying information about other concepts. This link is represented through a dotted arrow from the concept carrying the information to the supported information in Figure III-40. For example, the Dräger sensor is providing information to trigger the alarm.

To understand the impact of reality anchors on the human-decision making, those concepts and sub-concepts are identified in the experience feedback forms. The extraction of the concepts from the experience feedback forms is performed as presented in this example (see Example III.2).

Example III.2 Experience feedback analysis

The experience feedback in Figure III-41 can be decomposed as below:

- The first line refers to an **alarm** from an **acoustic sensor**,
- The time refers to the **date** of the event,
- 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**.

In the next lines other concepts can be identified like:

- An alarm from a **Dräger sensor** (gas concentration detector)
- The **date**,

- The **sensor type**,
- 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 III-41: Translated experience feedback form from the first scenario.

To analyze the results of the experience feedback forms, tables containing the number of appearances of each reality anchors-based concepts were defined for each scenario as well as for every scenario. These tables show three major types of results:

- The concepts that were used in the directed forms only are identified in **green** (see concept 3 in Figure III-42). Identifying those concepts shows reality anchors that are added as details of the situation.
- The concepts that were used in the free forms only are identified in **orange** (see concept 2 in Figure III-42). Identifying those concepts shows reality anchors that disappears 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.
- The concepts that were not used in any experience feedback forms are identified in **red** (see concept 4 in Figure III-42). Identifying those concept shows a lower priority in term of usages in the description of a situation.

Concepts	Free form		Guided form						Total				
	1	2	1			2			Free	Guided			Global
			Description	Analysis	Actions	Description	Analysis	Actions		Description	Analysis	Actions	
Concept 1	1	0	1	0	0	1	0	0	1	2	0	0	3
Concept 2	0	1	0	0	0	0	0	0	1	0	0	0	1
Concept 3	0	0	0	1	0	0	0	0	0	0	1	0	1
Concept 4	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure III-42: Example of experience feedback results table.

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

First scenario: low risk situation with detection confirmation

First scenario presents a situation of acoustic and concentration detection of a supposed medium size gas leak on the mezzanine deck. In this scenario, no permit is

currently being performed on the site and the weather is cloudy with a constant 7 knots wind. Results obtained on this scenario can be seen in Figure III-43. These results are obtained through the analysis of number of appearances of the reality anchor concepts in the free and oriented feedback forms.

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

Figure III-43: Experience feedback results for scenario 1.

The results for this scenario show the importance of the concepts linked to the alarms (acoustic sensor, alarms, Draeger sensor, etc.). Moreover, they also highlight the link between the anomaly detection system information and the equipment of the process impacted (equipment, and process concepts are used). This shows the ability of the tool to provide the user with an understanding of the situation.

The more detailed concepts show that the users are understanding the situation as they identify information like the confidence in the presence of a gas leak and the

nature of the gas leak. It also shows that operators can use the information linked to the context like the CCTV, the weather information and the pressure of the process.

Second scenario: low risk situation without confirmation

Second scenario presents a situation of acoustic detection of a supposed small gas leak on the upper process deck. In this situation a cold work permit has been delivered for a work close on the impacted deck and the weather is cloudy with a medium variable wind. The results obtained on this scenario are presented in Figure III-44. These results are obtained through the analysis of number of appearances of the reality anchor concepts in the free and oriented feedback forms.

Concepts	Free form		Guided form						Total				
	1	2	1			2			Free	Guided			Global
			Description	Analysis	Actions	Description	Analysis	Actions		Description	Analysis	Actions	
Acoustic sensors	1	0	1	0	0	0	1	0	1	1	1	0	3
Alarm stability	0	0	0	0	0	0	0	0	0	0	0	0	0
Alarms	1	1	1	0	0	0	1	0	2	1	1	0	4
CCTV	0	0	0	0	1	0	0	0	0	0	0	1	1
Cloud	0	0	0	0	0	0	0	0	0	0	0	0	0
Confidence	0	0	0	1	0	0	0	0	0	0	1	0	1
Date	1	3	0	0	0	0	1	0	4	0	1	0	5
Direction	0	0	0	0	0	0	0	0	0	0	0	0	0
Draeger sensor	0	0	0	1	0	0	1	0	0	0	2	0	2
Equipment	0	0	0	0	0	1	0	0	0	1	0	0	1
Flow rate	1	0	0	0	0	0	0	0	1	0	0	0	1
Gas leak	0	0	1	1	0	0	0	0	0	1	1	0	2
Hole dimension	0	0	0	0	0	0	0	0	0	0	0	0	0
Leakage position	1	1	1	0	0	0	0	1	2	1	0	1	4
Level	0	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0
Nature	0	0	0	0	0	0	0	0	0	0	0	0	0
Nature of permit	1	1	0	0	0	1	0	0	2	1	0	0	3
Number of alarms	1	0	0	0	0	0	0	0	1	0	0	0	1
Number of people	0	1	0	0	0	0	0	0	1	0	0	0	1
People in the vicinity	0	0	0	0	0	0	0	0	0	0	0	0	0
Permit	1	1	0	0	1	1	0	1	2	1	0	2	5
Permit date	0	0	0	0	0	0	0	0	0	0	0	0	0
Permit name	0	0	0	0	0	0	0	0	0	0	0	0	0
Permit position	1	1	0	0	1	1	0	0	2	1	0	1	4
Pressure	0	0	0	0	0	0	0	0	0	0	0	0	0
Pressure sensor	0	0	0	0	0	0	0	0	0	0	0	0	0
Process	0	0	0	0	0	1	0	0	0	1	0	0	1
Sensor name	1	0	0	0	0	0	2	0	1	0	2	0	3
Sensor position	0	0	0	1	0	0	0	0	0	0	1	0	1
Sensor status	1	0	0	1	0	0	1	0	1	0	2	0	3
Sensor type	1	0	0	2	0	0	1	0	1	0	3	0	4
Sensors	0	0	0	0	0	0	0	0	0	0	0	0	0
Severity	0	1	1	1	0	0	1	0	1	1	2	0	4
Weather	0	0	0	0	0	1	0	0	0	1	0	0	1
Wind direction	0	0	0	0	0	1	0	0	0	1	0	0	1
Wind speed	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure III-44: Experience feedback results for scenario 2.

As for the first scenario, the results show the importance of the concepts linked to the alarms as they are used in both form types. Moreover, a work permit is part of the

situation of this scenario. Therefore, the concepts linked to it are appearing (permit, nature of permit and permit position) and also considered important for the situation description.

The more detailed concepts show the information needed to create the user understanding of the situation and focus on the different concepts linked to the context of the situation. In this scenario, it also shows the importance of the lack of confirmation from multiple sources. This is deduced from the presence of the Dräger sensor concept in the directed experience feedback when no such sensors were activated.

Third scenario: repetitive acoustic detection without confirmation

Third scenario presents a situation of repetitive acoustic detection of a supposed very small gas leak on the upper process deck. In this situation no work permit has been delivered and the weather is cloudy with a high-speed wind. The results obtained on this scenario are presented in Figure III-45. These results are obtained through the analysis of number of appearances of the reality anchor concepts in the free and oriented feedback forms.

Concepts	Free form		Guided form						Total				
	1	2	1			2			Free	Guided			Global
			Description	Analysis	Actions	Description	Analysis	Actions		Description	Analysis	Actions	
Acoustic sensors	0	2	1	1	0	0	0	0	2	1	1	0	4
Alarm stability	0	2	0	0	0	0	0	0	2	0	0	0	2
Alarms	2	2	1	1	1	0	2	0	4	1	3	1	9
CCTV	0	0	0	0	0	0	0	0	0	0	0	0	0
Cloud	0	0	0	0	0	0	0	0	0	0	0	0	0
Confidence	0	0	0	0	0	0	0	0	0	0	0	0	0
Date	3	0	1	0	0	1	4	1	3	2	4	1	10
Direction	0	0	0	0	0	0	0	0	0	0	0	0	0
Draeger sensor	0	1	1	1	0	0	0	0	1	1	1	0	3
Equipment	0	3	0	0	0	1	0	0	3	1	0	0	4
Flow rate	0	0	1	0	0	0	0	0	0	1	0	0	1
Gas leak	0	0	0	0	0	0	0	0	0	0	0	0	0
Hole dimension	0	0	0	0	0	0	0	0	0	0	0	0	0
Leakage position	1	1	1	0	0	0	0	1	2	1	0	1	4
Level	0	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0
Nature	0	0	0	0	0	0	0	0	0	0	0	0	0
Nature of permit	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of alarms	0	0	1	0	0	0	0	0	0	1	0	0	1
Number of people	0	0	0	0	0	0	0	0	0	0	0	0	0
People in the vicinity	0	0	0	0	0	0	0	0	0	0	0	0	0
Permit	0	0	1	0	0	1	0	0	0	2	0	0	2
Permit date	0	0	1	0	0	0	0	0	0	1	0	0	1
Permit name	0	0	0	0	0	0	0	0	0	0	0	0	0
Permit position	0	0	1	0	0	1	0	0	0	2	0	0	2
Pressure	0	1	0	0	0	0	0	0	1	0	0	0	1
Pressure sensor	0	0	0	0	0	0	0	0	0	0	0	0	0
Process	0	1	0	0	0	1	0	0	1	1	0	0	2
Sensor name	0	0	0	0	0	0	4	0	0	0	4	0	4
Sensor position	0	0	0	0	0	0	0	0	0	0	0	0	0
Sensor status	0	1	1	1	0	0	2	0	1	1	3	0	5
Sensor type	0	2	1	2	0	0	0	0	2	1	2	0	5
Sensors	0	0	0	0	0	0	0	0	0	0	0	0	0
Severity	1	0	1	0	0	0	0	0	1	1	0	0	2
Weather	0	0	1	1	0	1	0	0	0	2	1	0	3
Wind direction	0	0	1	0	0	1	0	0	0	2	0	0	2
Wind speed	0	0	1	1	0	0	0	0	0	1	1	0	2

Figure III-45: Experience feedback results for scenario 3.

Looking at the results in this scenario, the same focus on elements linked to the anomaly detection system and the impacted equipment as in the first scenario can be seen.

A difference with the second scenario appears as the concepts linked with the work permits appears this time in the directed and more detailed experience feedback forms even though there is no current permit on the site. This phenomenon can be explained by the fact that the alarm is voluntarily unstable and therefore the user is not sure if a gas leak is present on the site or not and consider every possible element of the situation.

Fourth scenario: high risk situation with multiple detections

Fourth scenario presents a situation of acoustic and multiple concentration sensor detection of a supposed big gas leak on the process deck. In this situation a hot work permit has been delivered and is performed close to the detection point. Moreover,

the maintenance of the impacted equipment is late and the weather is sunny with no wind. The results obtained on this scenario are presented in Figure III-46. These results are obtained through the analysis of number of appearances of the reality anchor concepts in the free and oriented feedback forms.

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

Figure III-46: Experience feedback results for scenario 4.

Looking at the results in this scenario, the same focus on elements linked to the anomaly detection system and the impacted equipment as in most previous scenario can be seen. However, in this scenario, the concepts linked to the working permits and people in the vicinity are present in every forms. This shows the importance of the human being in dangerous situations.

Fifth scenario: medium risk situation with late confirmation

Fifth and last scenarios present a situation of acoustic followed by concentration sensor detection of a supposed medium gas leak on the upper process deck. In this situation a cold work permit has been delivered and is performed on the deck below the point of detection. Moreover, the weather is sunny with a medium speed variable wind. The results obtained on this scenario are presented in Figure III-47. These results are obtained through the analysis of number of appearances of the reality anchor concepts in the free and oriented feedback forms.

Concepts	Free form		Guided form						Total				
	1	2	1			2			Free	Guided			Global
			Description	Analysis	Actions	Description	Analysis	Actions		Description	Analysis	Actions	
Acoustic sensors	1	0	1	0	0	1	0	0	1	2	0	0	3
Alarm stability	0	0	0	0	0	0	0	0	0	0	0	0	0
Alarms	2	1	2	2	0	2	0	0	3	4	2	0	9
CCTV	0	0	0	1	0	0	0	0	0	0	1	0	1
Cloud	0	0	0	0	0	0	0	0	0	0	0	0	0
Confidence	0	0	0	2	0	0	0	0	0	0	2	0	2
Date	3	2	0	0	0	0	0	0	5	0	0	0	5
Direction	0	0	0	0	0	0	1	0	0	0	1	0	1
Draeger sensor	1	0	1	0	0	1	0	0	1	2	0	0	3
Equipment	0	1	1	0	0	1	2	0	1	2	2	0	5
Flow rate	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas leak	1	0	0	0	0	0	1	2	1	0	1	2	4
Hole dimension	0	0	0	0	0	0	0	0	0	0	0	0	0
Leakage position	0	1	1	0	0	1	1	0	1	2	1	0	4
Level	0	0	0	0	0	0	1	0	0	0	1	0	1
Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0
Nature	0	0	0	0	0	0	0	0	0	0	0	0	0
Nature of permit	1	1	0	0	0	0	0	0	2	0	0	0	2
Number of alarms	0	0	1	1	0	0	0	0	0	1	1	0	2
Number of people	0	0	0	0	0	0	0	1	0	0	0	1	1
People in the vicinity	0	0	0	0	1	0	0	0	0	0	0	1	1
Permit	1	1	0	1	0	0	1	0	2	0	2	0	4
Permit date	0	0	0	0	0	0	0	0	0	0	0	0	0
Permit name	1	0	0	0	0	0	0	0	1	0	0	0	1
Permit position	0	1	0	0	0	0	1	1	1	0	1	1	3
Pressure	0	0	0	0	0	0	1	0	0	0	1	0	1
Pressure sensor	0	0	0	0	0	0	0	0	0	0	0	0	0
Process	0	1	0	0	1	0	1	0	1	0	1	1	3
Sensor name	1	0	0	0	0	2	0	0	1	2	0	0	3
Sensor position	0	0	0	0	0	0	0	0	0	0	0	0	0
Sensor status	0	0	0	0	0	0	0	0	0	0	0	0	0
Sensor type	0	0	0	0	0	2	0	0	0	2	0	0	2
Sensors	0	0	0	0	0	0	0	0	0	0	0	0	0
Severity	0	0	0	0	0	0	0	0	0	0	0	0	0
Weather	0	0	0	1	0	0	1	0	0	0	2	0	2
Wind direction	0	0	0	0	0	0	1	0	0	0	1	0	1
Wind speed	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure III-47: Experience feedback results for scenario 5.

Looking at the results in this scenario, the same focus on elements linked to the anomaly detection system, the impacted equipment and the work permit as in previous scenario can be seen.

A number of precisions are appearing in the directed forms showing the information underlining the acquisition of situation awareness. Specific information in the form of the date and time of the alarms, the nature of permit and permit name are only appearing in the free feedback form.

Global assessment

After looking at the results of every specific scenario, they have been gathered to find general results regarding the use of the reality anchor concepts in the experience feedback forms. The results are presented in Figure III-48.

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 III-48: Experience feedback results for every scenario.

These results show that most information specifically used in detailed forms (in green) are not directly accessible information and are part of the user understanding of the situation. Moreover, it enables to identify data that are not used (in red) and might not carry meaning in the user situation model.

Query based form results

The query-based forms were used in this experiment to validate the ability from the users to find information and to understand it. The query-based forms are made of 21 queries regarding the description, analysis and projection of the situation and one free expression box for every category.

Results from the first scenario show no error or lack of information on the 21 queries. Moreover, the operator highlighted the lack of CCTV on the concerned floor as part of the analysis of the situation.

Results from the second scenario show a mistake in the identification of the number of permits. The operator identified 3 permits whereas there is only one permit that is to be performed by 3 persons. This mistake is probably a misunderstanding but show the ability from the operator to identify the presence of a permit to work on site. It would be interesting to ask the operator about this misunderstanding and correct it.

Results from the third scenario show no error or lack of information on the 21 queries.

Results from the fourth scenario show both a lack of information and errors. First, in the description section, the operator did not identify the wind speed even if the information is accessible in the dedicated section. Moreover, the operator identified 3 detecting sensors, forgetting to consider the 2 acoustics ones. However, when asked to identify the nature of the sensors, the operator identified correctly both the 2 acoustics and 3 CH₄ concentration sensors. This indicates that the mistake is not due to a lack of perception of the information but might be due to the operator not trusting on the technology. Secondly, in the analysis of the situation, the operator did not answer the information related to the impacted equipment, number of people in the vicinity and number of gas leaks as it did not consider having enough information to correctly assess these elements of the situation. Finally, in the projection of the situation, the operator misunderstood the question related to the identified risk and answered that he had identified them. In general, if this form was not answered as anticipated most answer showed an understanding of the situation by the operator and not a lack of access to information. However, regarding the wind speed, it seems that the operator did not have access to the information.

Results from the fifth scenario show no lack of information or mistakes apart from the fact that the operator did not answer regarding the gas cloud dimension and direction.

Overall, these forms showed the operator ability to access every implemented information related to the situation. Therefore, it validates the hypothesis that says that the operators accessed the information needed and that the reality anchors that does not appear in the previous experience feedback forms are not due to an inability to access the information.

Synthesis

In conclusion, 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 the information to be acquired in more detail. The secondary information is

identified as linked to the concepts of the impacted equipment and the people in the vicinity.

These results also validate the reality anchors identified in the elicitation step and their use in the acquisition of the situation awareness as no elements outside of the reality anchor list have been used to describe the situation.

As for the reality anchors that have not been used in the forms, three types of reality anchors appear. First, the concepts that are not usually used by operators like the maintenance. Second, the concepts that relates to the gas leak but cannot be easily identified like the size of the hole or the gas cloud position. Finally, the concepts that are part of the process and not considered specifically like the pressure sensors.

III.2.5.3 Activity analysis

In this experimentation the recording of the two screens was performed using a camera pointed at both screens. This method combines the recording of the user voice for the think out-loud technique and the recording of the movements of the pointer on the screen.

The thinking out-loud technique is widely used to enable to understand the reasons of the action performed by users (Klingert 1974; Olson, Duffy, and Mack 2018). It asks the users to detail their thoughts during the tests. If it is not usual for the users to define their thoughts and some may be missing (even more if the situation induce stress or reduced spare mental capacity), in most cases this enables to define the reasons behind the decision made by users.

The recording of the user pointer is used to translate their point of focus. This method is not ideal, as the user may be looking at other elements of the screen without pointing at it with the pointer. However, without access to an eye tracking system, this method enables to identify the main focus of the user attention on the prototype and define their uses of the displayed information.

The resulting recordings were analyzed using The Observer XT¹⁸, a behavior analysis software. This software enables to tag events and states on the videos timeline to extract a stamp-timed list of activities.

First a set of events and states were defined to be identified later in the video. To that end, the events and states were defined as it can be seen in Figure III-49. This definition of the events enables to identify different actions related to important elements like:

- The consultation of sensors (Dräger CH₄ &H₂S, acoustic) detailed and general information,
- The consultation of work permits global info,

¹⁸ <https://www.noldus.com/observer-xt> (accessed last 04/08/2022)

- The use of map icon,
- The consultation of CCTV images,
- The consultation of both maintenance states,
- The consultation of weather information.

As the interfaces have multiple views for both context and process screens, a set of state events were defined that enables to know at a specific point in time the interfaces consulted by the user. The consultation of specific points of interests providing constant information could not be accurately recorded. However, states event were defined to record the moments when the user is having its pointer on those elements. If not every consultation of those information where recorded this way, it gives a general idea of the usage of the information. To organize the experimentation process, the alarm activations were recorded using states events. This gives a general guideline of the experimentation course. Finally, specific actions like calling of the chief manager or the field operator or any process actions were recorded as well as point events.

Recording all these events enabled to define a global course of the experimentation and to represent activities.

Activity	Reference	Code	Type
Draeger	Global	S_Dräger_Global	Point event
	CH4_2002	S_CH4_2002	Point event
	CH4_2003	S_CH4_2003	Point event
	CH4_2004	S_CH4_2004	Point event
	CH4_2104	S_CH4_2104	Point event
	Ch4_2202	S_CH4_2202	Point event
Acoustic	H2S_Unique	S_H2S_Unique	Point event
	Global	S_Acoustic_Global	Point event
Permit global	Unique	S_Acoustic_Unique	Point event
		H_Permit_Global	Point event
Permit unquique	Hot work	H_Hot_Unique	Point event
	Cold work	H_Cold_Unique	Point event
CCTV global		CCTV_Global	Point event
CCTV unique	PD_SW_E	CCTV_PD_SW_E	Point event
	PD_SW_N	CCTV_PD_SW_N	Point event
	PD_NW_S	CCTV_PD_NW_S	Point event
	UPD_NE_S	CCTV_UPD_NE_S	Point event
State	Global	State_Global	Point event
Weather	Global	Weather	Point event
Process view	High prssure	B_Ballon_HP	State event
	Medium pressure	B_Ballon_MP	State event
Context view	Back to site view	Z_back_To_Site_View	State event
	Longitudinal view	Z_Longitudinal_View	State event
	Process deck view	Z_Process_Deck_View	State event
	Mezzanine view	Z_Mezzanine_Deck_View	State event
	Upper process deck	Z_Upper_Process_Deck_View	State event
Compass		Point_Compass	State event
Info_alarm		Point_Info	State event
Info_separator		Point_Separator	State event
experience		A_Exp	State event
Process leak		B_Leak_Process	Point event
Alarm	Acoustic	A_Acoustic	State event
	Alarm1	A_Alarm1	State event
	Alarm2	A_Alarm2	State event
	Alarm3	A_Alarm3	State event
	Alarm4	A_Alarm4	State event
Stop the process		Stop	Point event
call chief		Call_Chief	Point event
call operator		Call_Op	Point event
Aquit alarm		Aquit	Point event

Figure III-49: Set of events and states used during the activity analysis.

The recorded results were extracted in a single global table. The recorded events were transformed in a set of well-defined activities following as set of verb, type, and complement (see Figure III-50) giving a common set of activities to be compared between operators and scenarios. This enables to define the result table seen in Figure III-51.

The ratio of availability

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 conclusion on their role in the decision-making process.

Looking at the example in Figure III-52, the first reality anchor is the name of the sensor and its date of activation. This anchor is available in 6% of the actions performed by the user. This means that this information is used but as it is a detailed information available through a specific action it is not a main information needed for the decision-making process.

In comparison, the second anchor, the sensor position, type, and status, is available in 65% of the activities. This anchor is present on the map where the leak is detected, and its high availability ratio means that the user is aware of the leak position and make is decision by using this information.

Scenario	Anchor	Availability ratio		Analysis
		Operator	Ratio	
1	Dräger1_name_date	1	5,71%	The anchor is not much available. The fact that this anchor is only available as detailed information on a sensor can explain this phenomenon. This anchor is therefore only used as detail but is not a main need for the decision making process.
		2	0,00%	
		3	7,14%	
		4	5,26%	
		5	12,50%	
		Global	6,12%	
1	Dräger1_position_type_status	1	48,57%	The anchor is mostly available. This anchor is available as the user is on the deck map where the alarm is. This means that the user is aware of the sensor position. However, some values are lower for user 1 and 4. This might be explained by a change in the map performed by these users (for example to check on the process values).
		2	72,73%	
		3	78,57%	
		4	47,37%	
		5	62,50%	
		Global	65,95%	

Figure III-52: Extract from the analysis.

Taking a global view of the availability ratio have been assembled in a global table (see Table III-7) to define general conclusions. The reality anchors always available on the screen are presented in grey and the reality anchors that need to be accessed for decision making are presented in white. Looking at the results, it is possible to draw some general conclusion regarding the availability of the reality anchors.

Regarding the sensors, the detailed information like the name of the sensor is very rarely used by the users while making a decision. However, the other related information that are 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 action having the leakage point available to them.

The other leak detection related reality anchors (that have to be accessed) have been available to the user at least once and even show more than 20% of availability for some user. This highlights the importance of these reality anchors.

Reality anchors related to permit to work shows to be at least available once for most user even when no permit is currently being performed on site. This shows the importance of these reality anchor. Recommendation could be to make constantly available to the user the number of permits currently performed on site. This will enable the user to know if he needs to access more information or not.

Reality anchors related to the equipment show a low ratio of availability. These results show that not much interest is being given to the equipment details 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 them available while making their decision. This shows that, as for the maintenance reality anchors, these could be discarded if needed.

CCTV reality anchors were simulated and therefore not very realistic enough to decide in the situation. However, it was asked to the user to access that information nonetheless if they wished to have them available. The results show that user accessed that information and that this reality anchor need to be conserved.

Finally, the ratio of availability of the process related reality anchors shows the importance of the tool to keep the direct link with those reality anchors.

Table III-7: Results of the availability ratio study.

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			
Draeger 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%	0%	6%	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_equipment	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%			
Equipment	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%			
Weather	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%	0%	3%	0%	10%	0%	0%	0%	0%	5%	7%	0%	0%	0%	0%			
	Humidity	0%	9%	0%	0%	0%	0%	0%	0%	0%	3%	0%	10%	0%	0%	0%	0%	5%	7%	0%	0%	0%	0%			
	atm_pressure	0%	9%	0%	0%	0%	0%	0%	0%	0%	3%	0%	10%	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%			
	Pressur_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%				

To go further in the reality anchors availability study, the cumulative availability of the reality anchors is studied in the next section.

The cumulative availability

Regarding the final analysis phase, figures were defined to show the growing list of anchors that have been available to the user (see Figure III-53). These figures aim at showing how users acquire a set of reality anchors having been available to them until they decide.

Part III: Oil-and-gas use case: Gas leak on off-shore rig decision making

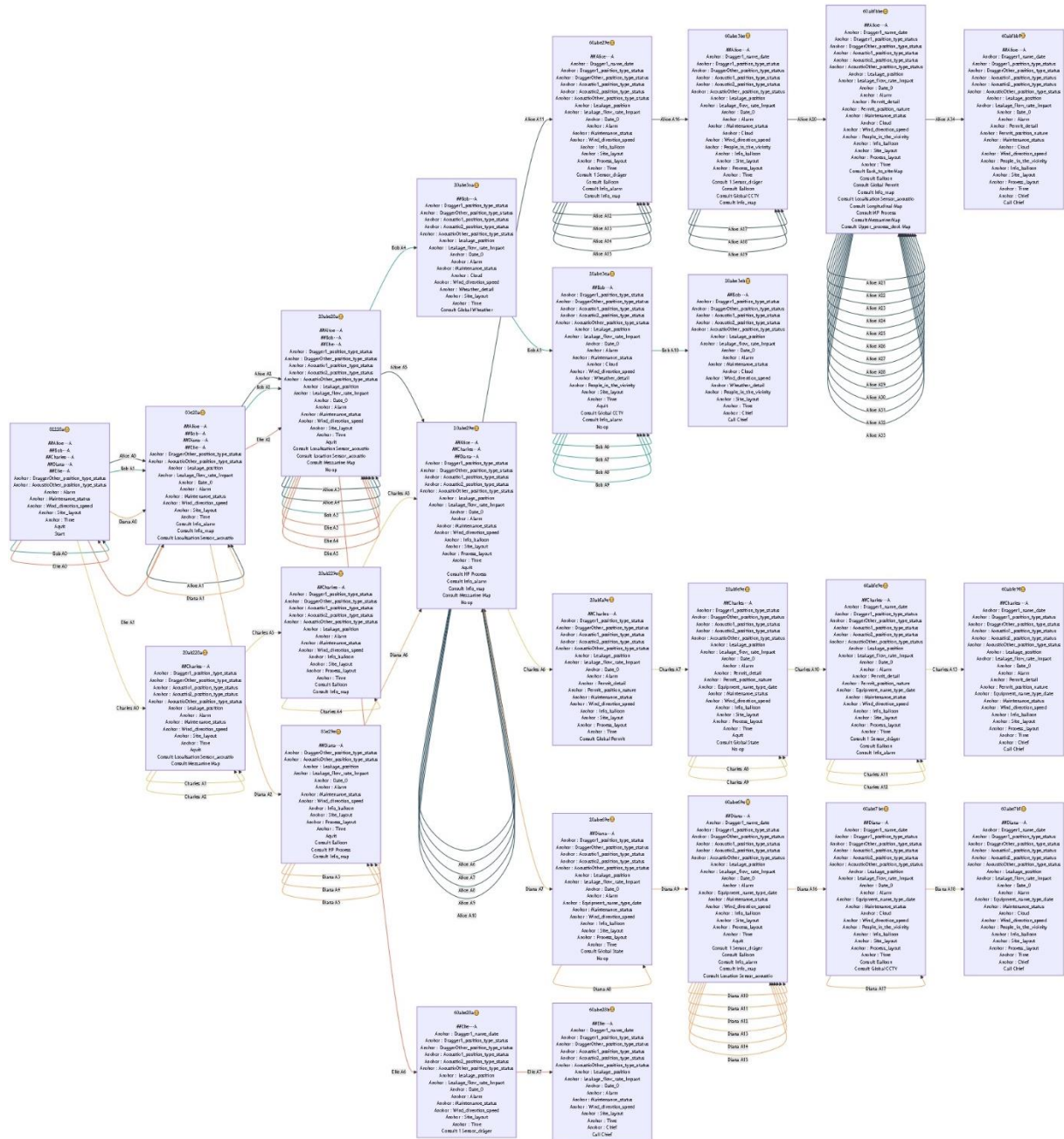


Figure III-53: Cumulative reality anchor analysis chart for the 5 operators on scenario 1.

Comparing operators cumulative use of reality anchors on each scenario, no general logic for the full process appeared. Every user performs a different information accessing pattern and the decision is performed with various type of information being acquired. If the total amount of consulted information is different for every tester, a set of minimum information can be identified.

The reality anchors that have been accessible for every tester when they make decision are (see Figure III-54):

- The leakage flow rate and estimated impact,
- The current time,

- The maintenance status of the equipment,
- The position, type and status of the acoustic sensors that have detected an anomaly,
- The position, type and status of the acoustic sensors that have not detected any anomaly,
- The wind direction and speed,
- The leakage position as reported by the acoustic sensors,
- The site layout,
- The alarm visual and audio signal,
- The position, type, and status of the Dräger sensors that have detected anomalies,
- The position, type, and status of the Dräger sensors that have not detected anomalies,
- The permit position and nature.

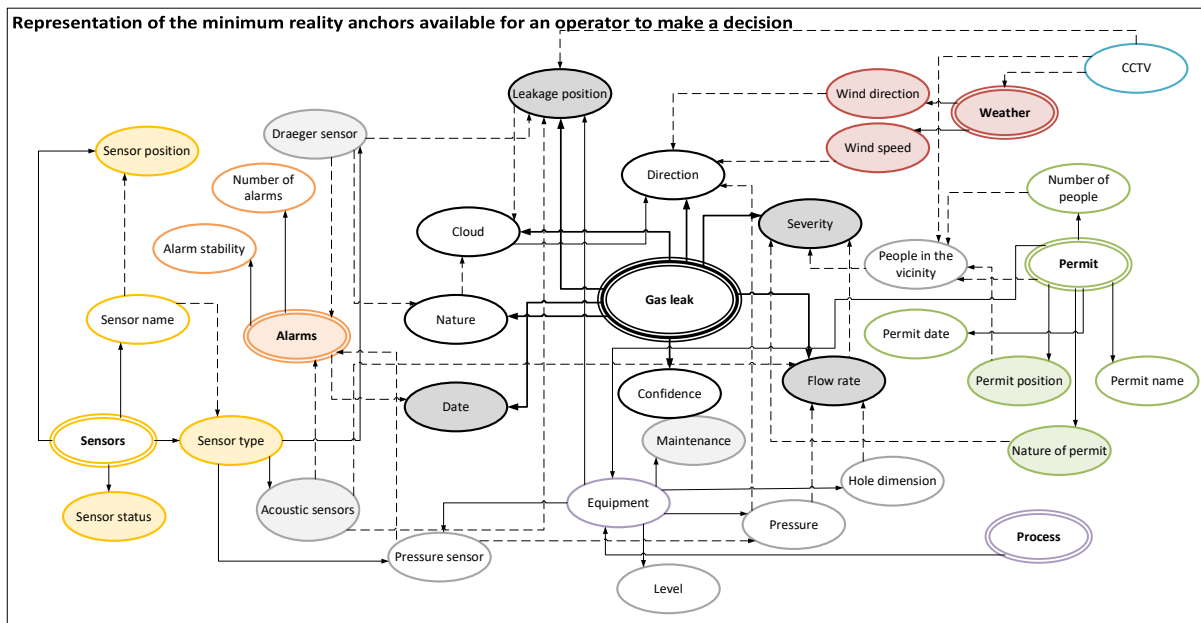


Figure III-54: Representation of the minimum reality anchors available for an operator to make a decision.

Out of these reality anchors only the information regarding the leak flow rate and estimated impact were not directly available by looking at the map corresponding to the leak position. It therefore can be said that the minimal reality anchors needed for operators to make decision were already contextualized and made available to the user with exception to the specific information related to anomalies (leak flow rate and estimated impact).

Other results can be extracted from these figures. The first information acquired is the same and concerns the gas leak characteristics. This indicate that the user first focus on the anomaly detection related information. This phenomenon goes along with the focus from the testers in the experience feedback forms (see section III.2.5.2).

Finally, the results showed that some activities performed on the interface do not allow access to more reality anchors. This shows the need for users to consolidate their perception by reconsulting some information. This phenomenon can also be due to the fact that only availability is recorded and not the perception of the information and that several anchors are available at the same time, but users might focus only on some specifics.

Synthesis

In conclusion, the successive analysis of the results from the activity recording enabled to have a partial image of the use of the reality anchors by the testers.

First, the ratio of availability of the reality anchors have enabled to identify the reality anchors not used by testers. It also made possible to analyze individually the usages of the reality anchors for each scenario.

Then, the successive availability of the reality anchors showed the successive states of reality anchor availability for each scenario to identify a pattern. However, with the activity recording made in this experimentation, pattern cannot be identified.

Finally, the cumulative availability of the reality anchors has showed that testers tend to access the same anchors related to the detection information at the beginning of every scenario. It also highlighted the need for tester to perform actions that do not provide more access to reality anchors and therefore is used to re-access information or consult information already available but not used previously (to possibly refine its situation awareness and its decision). Looking at the global process of reality anchors cumulative availability, it shows that every tester decides after having access to different reality anchors. Moreover, it enabled to identify the main set of anchors needed at the minimum to decide.

III.2.5.4 Results analysis synthesis

In conclusion, the results from the use of the SART provided sign that the prototype implementation and testing was performed in a realistic and familiar ways. This validate the results as being used to improve on the tool design. Moreover, the same results have shown the ability for the prototype and the used reality anchors to provide a global view of the situation without creating mental overload. This is topped by the insight that fast evolving situations impact the user complexity rating and that improving access to the reality anchors most used by user can provide support for the situation awareness process.

To improve on this process, the results from the experience feedback forms and the activity analysis have enabled to identify most important reality anchors, unused ones and the ones lacking from the prototype (like the process trends and CCTV). These two

sources of results have shown the focus from the tester on information related to the anomaly, the equipment, and the personnel on site.

Moreover, some reality anchors could not be implemented in the prototype, like the process KPI trends, but were called out as missing by the testers.

The next and last step of this methodology aims to address these results to ensure the designed SASS correspond to the user.

III.2.6 Results application to SASS

Based on the results defined in the previous study, the SART results showed that the prototype and the scenario were familiar enough to tested out the impact of the tool. Therefore, no changes will be done to the scenarios. However, improvements must be made to ensure the best ability from the SASS to support SA. These improvements should be implemented on the prototype and tested out through a new set of tests with users.

The improvement identified in this use case are the following:

- The results identified a focus from the testers on the information related to the anomaly detection. This will be tackled through the enlargement of the space dedicated to this information as asked by testers.
- The results identified a lack of use for the information related to equipment maintenance. However, a high number of such information is made available on the tool. This information can therefore be brought out of the tool to enable the user to focus more easily on important information.
- The results identified a lack of KPI trends that are considered as needed by the user. Therefore, this reality anchors will need to be implemented in the next iteration of the prototype.
- The results identified the importance of information related to the human positions on site during the anomaly management. To improve on this field, new ways to gather information on the human positions on site should be researched to improve the information quality for users (like geolocation for example).

At the state of this thesis, these modifications have been identified but not implemented in the tool as time is lacking to do so. Once implemented, tests with new users should be performed to identify the impact of the prototype on the user.

III.3 Discussion on the results of the RAM application

If the deployment of the RAM methodology on the oil-and-gas use case aimed at providing results for the implementation of a digital twin for the gas leak management, it also provided highlights on the applicability of the methodology. The ability for this methodology to provide results are discussed in the next sections.

III.3.1 Discussion on the results and limits of this methodology

The application of the methodology to the oil-and-gas use case provided results to work with but showed limitations. These limitations lie in the uncertainty that accompanies testing with humans and in the medium used to record results.

Working with human expert means having access to them. Specificity of control room operating environment, where operators are required fully focused do not allow 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 longer than expected.

Regarding the tools used to capture the results, the absence of eye tracking device forced us to work on the availability of the reality anchors and not their perception by the user. The results are therefore holding on a major assumption that the tester used the reality anchors made available to them. 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 contextualized 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 enabled to show the impact of the tool on situation awareness and to give insight on how to improve the prototype to develop a tool answering to the user needs.

III.3.2 Response to the problem

This methodology could not be implemented to completion in the industrial domain due to time constraints. However, as we have shown it in this part, the methodology was implemented up until the human-in-the-loop testing. This provided a clear picture of the methodology's ability to meet the objective of designing a Situation Awareness Support System to support real-time decision-making in abnormal situations.

Based on the results obtained in the first iteration, the defined reality anchors matched the user's needs. Furthermore, the SA evaluations recorded in the SART results showed the ability of the implemented prototype to support user's Situation Awareness (SA). Therefore, the proposed methodology meets the identified objective. Moreover, the results are currently being used at TotalEnergies to develop a decision-making support tool.

Conclusion

In this section, we applied the Reality Anchor Methodology to a use case from the oil-and-gas domain. Focusing on the control room operator's decision making during the management of a gas leak situation, the methodology was applied to design a digital twin to be implemented in the control room to provide operators with situational awareness.

To do so, rules and procedures from the company were studied to define a decision-making process. To refine this process, interviews with operators were performed. These interviews enabled to define a more detailed process and to extract the reality anchors used by operators to acquire situation awareness. These reality anchors were almost all implemented in the prototype that simulates a control room digital twin. This prototype was then evaluated through the eyes of five operators with experience from the domain.

The evaluation of the Situation Awareness using the Situation Awareness Rating Technique enabled to validate the effect from the prototype on the tester situation awareness. Moreover, the use of experience feedback forms and activity analysis enable to identify the changes to be performed to improve on the reality anchors availability.

If the methodology could not be applied all the way, it validated its ability to be applied with positive results to design a Situation Awareness Support System.

Conclusion and perspective

The recent advances around the Digital Twin (DT) concept and its applications to industrial problems offer new opportunities for better management of complex industrial systems. In this PhD work, a DT is used as a Situation Awareness Support Systems (SASS) and the interactions between human operators and this SASS are studied to ensure the relevance of this use of a DT.

As the complexity of industrial systems grows, the need to ensure usability and understandability of those systems become prominent. To answer those challenges, the use of Human Systems Integration techniques and a focus on the human situation awareness directed this study. The human Situation Awareness (SA) acquisition is defined as a major phase in the decision-making process. Composed of three levels, that are the perception, comprehension, and projection, the acquisition of SA needs to be ensured through decision support system called SASS.

To define a design methodology for SASS implementation, the approach presented in this manuscript is divided in three main parts.

The first part of this study clarified the definition of complex systems as a set of components whose aggregation makes it difficult for the user to understand and make decisions. Looking to support the users in their decision, the models of decision making have in common the situation assessment as a first step. Considering this, a focus on Situation Awareness Support Systems has shown that a dynamic digital model of the situation is a critical component in those systems. Hence, the SASS can be seen under the paradigm of a digital twin with its holistic model of the system and its situation. Indeed, we defined the digital twin as *a dynamic representation of a physical system using interconnected data, models, and processes to enable access to knowledge of past, present, and future states to manage action on that system*. The study of digital twin models in the literature proposed a seven-component digital twin structure to support decision support capabilities.

Designing (Human) Situation Awareness Support Systems for (Engineered) Complex System requires a design methodology that has a strong foundation in human-centered design and systems engineering. Among them, the Human Systems Integration paradigm which studies the interactions between humans and complex systems and provides guidelines to integrate both, has been chosen. For this reason, this study offers a design methodology focused on defining user needs and testing out their integration through human-in-the-loop simulations and appropriate formative evaluations. This study showed the need for stages enabling the definition of user needs, stages enabling the tests of implemented needs and the evaluation of the impact of the tool on the user. However, no methodology can provide a fully detailed process and encapsulate the cited stages. To address this gap, a methodology based

on the concept of reality anchors was defined. The reality anchors are defined as useful *elements of the situation necessary for humans to enable them to grasp reality and acquire a meaningful situational awareness that supports the decision-making process*. This methodology starts with the definition of the user needs through company rules study and interviews. From those, the Reality Anchors are defined. Then to ensure the validity of the defined Reality Anchors, a prototype is implemented and tested with final users from the domain. The defined Situation Awareness Support System prototype impact is finally evaluated using a combination of a Situation Awareness evaluation techniques, experience feedback forms and an activity analysis. The results enable to iterate on the prototype until the results needed are obtained.

In the third part, the Reality Anchor Methodology is applied on a use case extracted from the oil-and-gas domain. The gas leak management in an off-shore platform control room was selected as the use case. In this use case an abnormal situation management process was defined based on the TotalEnergies company rules and regulations. This process established the basis to formalize an interview protocol. These interviews, performed with eleven operators from the domain, enabled to formalize the process performed by control room operators to manage a gas leak. Moreover, this study enabled to define a total of 29 reality anchors. Those were implemented in a control room digital twin prototype and tests were performed using the Wizard of Oz principle. Experience feedback forms completed by testing operators revealed the use of information related to the leak characteristics and the way it was detected as the main elements to describe a situation. More details contained mainly information related to equipment and personnel in the vicinity. The Situation Awareness Rating Technique was used to assess self-perceived Situation Awareness of testing operators. The results showed that the operators situation awareness rating followed the awaited results on the different defined scenarios. Finally, the activity analysis has showed the focus from operators on leak related information as a first step. These results enabled to direct further improvement on making leak detection related information more present on the tool to facilitate its acquisition by the user. However, due to a lack of time, iterations on prototype could not be performed.

This work offers numerous perspectives for future work.

In the short term, it appears interesting to try and capture activities through an eye-tracking system. As seen in part III section III.2.4.1, the capture of the activity has been performed by filming the user screen using a camera. However, as stated in part III section III.3.1, this acquisition method is not optimal. Therefore, it would be interesting to perform the user test and specifically the activity recording using an eye tracking system. The system would be provided to the user at the beginning of the test and would record the user focus point. Analyzing the results would enable to work on the

information that have been looked at and not just the information that were available. This should bring more precision as to what information are used in which order. This should also enable to find information research patterns and optimize the Situation Awareness Support System interface.

Moreover, as stated in part III section III.3.1, no iteration and further testing could be performed to validate the recommendations captured from the first tests. This iteration is the last step of the Reality Anchor Methodology (RAM) and performing it would enable to test out the methodology fully. To finalize this implementation information should be reorganized in the prototype following the defined recommendations (implementation of new reality anchors, deletion of the unused ones, highlight of the information related to the alarms, etc.). Then, new tests should be performed with new operators and/or new scenarios. Test results should show better results in terms of situation awareness and may reveal new ways to improve the system.

In the medium term, the prototype should be transformed into a fully fleshed product for TotalEnergies. This production step will bring new technical challenges. Firstly, a digital model of the site must be implemented. This model should provide a process view as well as a contextual view of the site and contain all the reality anchors previously defined. Moreover, this digital model must be connected to the site through sensors and actuators. Ensuring that data connect from one to the other will be challenging. In addition, the sensors, actuators and digital model will generate data and information that should be managed by the digital twin. Therefore, the implementation of a data bank is necessary. Finally, the defined tool must comply with regulations to be implemented on site. These challenges are already being tackled in parallel by the research and development team from the TotalEnergies company and shows great results in term of model implementation and data connection. Moreover, the regulation validation should soon enable the team to test out a prototype on an industrial site.

Finally, in the long term, the Reality Anchor Methodology (see part II section II.3) should be applied on other use-cases as its design extends beyond an application in the oil-and-gas domain. Applying the methodology to other systems should enable to form general recommendations regarding the Reality Anchors definition and their implementation to support Situation Awareness Support System designers. Reality anchors categories based on the domain of application might emerge along with general rules for their implementation in systems interfaces.

This work also highlights numerous perspectives in regards of the application on the digital twin concept as a Situation Awareness Support System.

The methodology focused mostly on supporting the perception level of the Situation Awareness process through the implementation of the reality anchors in the system.

However, previous studies have shown that sharing information and knowledge to the user supports the comprehension and projection levels (Endsley 1988). Looking at the digital twin as defined in this study (see part I section I.3.3), it appears that digital twins could be used to generate information and knowledge and support even more the user Situation Awareness. For example, this could be performed by adding information sources to the digital twin (see part I section I.2.3) or by using new data management algorithms like Bayesian network (Li et al. 2017), artificial intelligence (Beal et al. 2021) or machine learning (Chabanet, Bril El-Haouzi, and Thomas 2021).

Going along with the concept of distributed situation awareness, unplanned events during the testing showed interactions between operators and managers and the use of the digital twin for cooperation. Therefore, if this work focused on a single user, future works could take interest in the cooperation between users. Incorporating the notion of distributed situation awareness (see part I section I.2.2.3), design principles for cooperation (Pacaux-Lemoine et al. 2022) and the defined reality anchors methodology could enable to update the methodology defined in this work to support cooperation through distributed situation awareness. The defined reality anchors from this new point of view could enable to ensure distributed situation awareness and support cooperation through the use of digital twins.

Furthermore, considering the human cognitive process of situational awareness, the use of the memories to generate knowledge and enable the process as well as the distributed view of Situation Awareness raises the question of using experience feedback to generate a Situation Awareness in support systems. It would be interesting to study the capabilities for a digital twin to generate formalized experience feedback (Kamsu Foguem et al. 2008; Villeneuve et al. 2012). Being a medium for the user to acquire information, and represent a situation, it should contain every possible information needed to formalize experience feedback from managed past situations. Coupling such experience feedback with data management algorithms like Case-Based Reasoning (CBR) (Perner 2001) could generate knowledge to support the user.

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