Human Machine Interface for supporting sensemaking in critical situation; a literal review

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The maritime industry is changing rapidly with constant introduction of new technology. Dynamic positioning, a computer-controlled system to maintain a vessel's position and heading, is an example of this trend. This paper is a literature review to answer the research question: *What are the characteristics of Human Machine Interfaces (HMIs) that can support sensemaking in critical situations?* HMIs have a key role in supporting the operators in safety-critical situations, and the aim was to investigate this in order to lay the foundation for how to design HMIs in the future maritime context. Very few authors describe HMIs in the context of sensemaking. Based on Weick's work on sensemaking, we grouped the literature identified according to his dimensions to establish the link to HMIs and operation of safety-critical situations in high-risk industries.

Keywords: Sensemaking, Human Machine Interfaces, safety critical situations, control centers, decision making.

1. Introduction

1.1 *Background*

Increasing digitalization is a feature characterizing high-risk industries, and the operators play a key role in critical situations. To make the right decisions to solve unexpected anomalies or crises, operators need to make sense of the situation. However, sensemaking becomes more difficult in critical situations, when sensemaking is really essential. Often, lack of suitable support for the human cognitive capabilities is recognized as a contributing factor behind incidents, see for example Leva et al. (2015). Thus, the Human-Machine Interface (HMI) is instrumental to cope with safety-critical situations.

This study is carried out in the framework of the project "Sensemaking in safety-critical situations" (SMACS). The objective of the project is to build and disseminate knowledge on how to enhance human, technical and organizational capabilities to handle safety-critical situations. A secondary objective is to develop an approach for Human Machine Interface (HMI) design supporting sensemaking and resilience, targeted to the maritime field.

1.2 *Purpose and research question*

The research question was: What are the characteristics of Human Machine Interfaces (HMIs) that can support sensemaking in critical situations? The focus is on HMIs in process control, especially in high-risk industries.

1.3 *Scope and definition*

The maritime industry is the target application domain in SMACS, and the main case is dynamic positioning. Nonetheless, we include experiences from other high-risk industries, including control rooms for nuclear power plants, ship bridges etc., all denoted control centers. In the following we define the key terms of this study.

1.3.1 *Safety-critical operation*

As a part of SMACS, Kilskar, et al (2018), documents a literature review focusing on the relationship between sensemaking and resilience. In this paper we adopt the same definition of "safety-critical" as Kilskar et al. (2018, pg. 2): "*to denote situations or operations that, if they go wrong, have a large potential for causing harm to people, property or environment*".

1.3.2 *Sensemaking*

The term "sensemaking" (also spelled sense-making, sense making) is used in different fields, from human computer interaction via human factors and to organizational sciences. It is widely present in the organizational management literature, where the concept emerged in the 1960s, and it has ever since been recognized as a

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central activity in organizations (Maitlis and Christianson, 2014). In the attempt to cover many, essentially similar processes occurring in organizations, the concept has grown very general and abstract.

In 1995 Karl E. Weick wrote the book *Sensemaking in Organizations,* and this work has influenced the sensemaking literature ever since. He described seven key elements of the sense-making process. In 2009, he listed the seven dimensions and proposed a range, as summarized in the following table. (Weick, 2009 page 62):

Table 1. Sensemaking dimensions.

Dimension	Range
Cues	Equivocal vs. confirmed cues
Social	Social vs. solitary resources
Plausibility	Possibility vs. probability as criterion for narratives
Enactment	Enactive vs. reactive as form of actions
Retrospective	Backward vs. forward noticing
On-going	Continuous vs. episodic flow of events

For each dimension the range describes to which extent ambiguity can be reduced, which is a key function of sensemaking. These dimensions are used in the categorization of papers in this paper. Maitlis and Christianson (2014 pg 67) provides an extensive overview of sensemaking literature and synthetize the following definition, particularly interesting for process control:

"[sensemaking is] a process, prompted by violated expectations, that involves attending to and bracketing cues in the environment, creating intersubjective meaning through cycles of interpretation and action, and thereby enacting a more ordered environment from which further cues can be drawn."

In a control centre, tasks like monitoring, decision making, planning, and resource coordination take place continuously. In normal circumstances those tasks are well organized, supported by consolidate knowledge of the domain, procedures and practices. In other circumstances a sensemaking process is necessary to adapt the behaviour of the entire system, operators and machines, to achieve good performance. Typical for such situations is the presence of ambiguity at many levels, for example because of unreliable information, vague procedures or uncertainties about consequences of actions.

1.3.3 Human Machine Interfaces

Evolution of Human Machine Interfaces (HMIs) has historically been technology driven. However, the increased understanding of human factors has transformed the principles behind design and quality criteria for HMI. The development has been from traditional interfaces, which were essentially computerized versions of the hard-wired wall panels, to more advanced interfaces with novel visualization like task-based. User-centered approaches to design are emphasizing the efficiency and precision in executing control actions.

The understanding of fundamental cognitive processes like perception and attention has led to a solid set of principles reflected in many industrial standards, e.g., NUREG-0700 (2002).

Today it is accepted that a good HMI cannot be designed without a deep understanding of the task, and context in which it operates (Leva, 2015). Human performance in terms of HMI usability, workload, and task efficiency is paramount in HMI design. In this paper we investigate how the dimensions of sensemaking are taken into consideration in HMIs.

2. Method

We have based our literature reviews mainly on bibliographical search engines like Google Scholar, Science Direct and Scopus. Keywords for the searches were: "sense*making", "safety critical" and "Human Machine Interface", and variants of HMI, like Human System Interface, Human Computer Interaction, and Man Machine Interface. Keywords should appear in Title or Abstract or as Keyword. From the obtained results we selected the articles best fitting our questions by reading the abstracts. We gave precedence to more recent papers expecting that, in line with the history of HMI, design is moving to face support for higher cognitive functions in more recent times.

We have integrated the survey with other sources of information, like seminars and conferences. After selection of relevant material from different sources we looked at the papers through the lens of the seven elements of sensemaking by Weick (1995).

3. Findings and discussion

The literature review by Kilskar et al. (2018), focused on the relationship between sensemaking and resilience. Their main finding was that "Few authors provide descriptions that characterize sensemaking in safety-critical situations." (p. 1). Similarly, in our case, a direct search combining sensemaking, HMI, and safety-critical situation gave very limited results. We believe this is due to a different usage of the terms in different disciplines. The concept sensemaking is mainly developed in organizational sciences, while the related term Situation Awareness (Endsley, 1995) is more known in the Human Factors (HF) field. The term HMI is also typical in human factors. In computer science the term Human Computer Interaction is more widely used, where normally the interface considered is on a general computer and not a device for controlling a technical system, as relevant for HF in process control.

3.1 *Sensemaking and situation awareness*

"Situation Awareness" (SA) is among the most commonly used terms to describe the link between HMIs and human performance in technology-heavy, safety-critical domains such as power plant control rooms, aviation and military operations. Endsley and Jones (2012) divides SA in three separate levels: "Level 1 – *perception* of the elements in the environment, level 2 – *comprehension* of the current situation, and level 3 – *projection* of future status."

When comparing SA to sensemaking (Endsley et al, 2015) Endsley concludes that sensemaking is generally retrospective in nature (only including level 1 and 2 of SA) while SA is more forward looking and anticipatory, and that the way sensemaking recognizes situations "*is characterized as primarily of the conscious deliberative type*", whereas SA also covers more automatic or faster responses to quickly emerging situations. Endsley thus regards sensemaking as a subset of SA.

Klein et al (2006) on the other hand states that "Endsley's work on situation awareness is about the knowledge state that is achieved – either knowledge of current data elements, or inferences drawn from these data, or predictions that can be made using these inferences. In contrast, sensemaking is about the process of achieving these kinds of outcomes, the strategies, and the barriers encountered." Klein et al. then go on to list a number of functions that sensemaking serves, including both "retrospective analysis of events" and anticipation of the future, thus supporting action. Other authors indicate sensemaking as a broader strategic concept supporting SA (Kilskar et al., 2018: p. 4). Whichever specifics one adheres to, overlaps between the two terms are clear. We therefore conclude that HMI characteristics that support situation awareness are at least highly relevant for making sense of the same situation.

3.2 *Literature grouped according to Weick*

Given the key role of sensemaking in critical situations, where a high level of ambiguity is present, we are interested to see how the HMIs support the seven elements of sensemaking. We have grouped the papers in this literature review according to the dimensions of Weick, although many of the papers touch upon several of the dimensions in various ways. The first column in the table below indicates the main dimension.

Dimension	Author(s)	Year	Publication type	Topic, relevance to HMI
plaus	Boring	2014	Conference paper	Future work for Human Reliability Assessment methods. Most used Today's methods were not designed to deal with Digital interfaces
enact, id	Borst et al.	2015	Journal paper	Beyond Ecological interfaces design, overcome misconceptions for supporting productive thinking.
soc	Braarud et al	2015	Conference paper	Measuring multi-dimensional performance, including situation awareness, workload, task performance, and teamwork
cue	Carrol	2015	Journal paper	Ambiguity and multiple perspectives
plaus	Culen	2014	Conference paper	Assisting sensemaking, collaborative processes providing HMI supporting visual reasoning
cue	Dahlberg	2015	Journal paper	Exploration of resilience and complexity, balancing the required variety for shaping resilience and increments of complexity
cue	Dorton and Thirey	2017	Journal paper	Effective Variety, a folk theory to understand the characteristics HMI should have to present operator the 'right level' of complexity. Derived from Requisite Variety.
plaus	Favarò and Saleh	2018	Journal paper	Temporal logic for safety supervisory control and hazard

cue	Flach	2017	Journal paper	Emergence of Cognitive System engineering: Abstraction hierarchy, Decision ladder (Skill-Rule-Knowledge), Ecological Interface Design and proactive risk management.
on-going	Giraudet et al.	2015	Journal paper	Information via auditory channel cognitively demanding tasks whilst confronted with temporal pressure, stress, and high-risk decision-making
plaus	Groen et al.	2017	Journal paper	Crisis Management. hybrid human–agent systems sharing information to create a situation assessment enabling reasoning and decision support.
enact	Howard	2012	Conf. paper	Intention awareness in joint cognitive system
enact	Inagaki	2010	Article	Joint cognitive systems, authority and responsibility in advanced driver assistance system, over-trust overreliance issues.
cue	Landman et al	2017	Journal paper	Unexpected events. Startle and surprise. Complex and unclear interfaces as factors making the pilot's reframing difficult
id	Liu et al.	2016	Journal paper	Real-time detection of the pilot's physiological and cognitive states for better interaction
cue	Madsbjerg	2017	Book	Bringing back the human at the center of sensemaking
enact	Mahajan et al	2017	Journal paper	Systems Theoretic Process Analysis (STPA), for inclusion of system-level causal factors by focusing on component interactions. hazard analysis techniques are not designed to identify hazardous states caused by system interactions
cue	Malakis and Kontogiannis	2012	Journal paper	Framing and reframing a mental picture of a situation in controlling air traffic. Data/frame theory.
retr	Pazouki et al.	2018	Journal paper	Increasing level of automation and its impact: ineffective monitoring, degraded situation awareness, subtle automation failures
plaus	Porthin et al.	2016	Research report	A Literature review of methods for Human reliability assessments for Digital control rooms.
cue	Ranking et al.	2016	Journal paper	The re-framing process after surprise
retr	Rosness et al.	2015	Open access	Considering the role of plausible projections of what can happen in sensemaking. Perspective sensemaking
enact	van de Broek et al.	2017	Conference paper	Autonomy in the maritime domain, new approaches to human machine collaboration
soc	Van Diggelen et al.	2018	Journal paper	Human centered approach for Dynamic Positioning system, combining multi technologies
soc	Vilim et al .	2015	Conf. paper	Operator support system with automated reasoning to determine plant states

3.2.1 *Cues*

Extracted cues provide points of reference for linking ideas to broader networks of meaning and are "*simple, familiar structures that are seeds from which people develop a larger sense of what may be occurring*." (Weick, 1995: p. 50).

Human expertise is characterized by the ability to select features to look at, to capture relevant cues from a massive amount of information.

In a modern control center, the massive amount of information presented to the operator has been filtered, integrated, and processed in many ways, it is a mediated reality. The information landscape surrounding the operators is in continuous change, operators see the process through a representation of models and numbers. Madsbjerg (2017 - loc 57) points out that an excessive attention to abstract model "*erodes our sensitivity to the nonlinear shifts that occur in all human behaviors and dulls our natural ability to extract meaning from qualitative information*".

Complexity is a source for ambiguity in cues, i.e., in the equivocal range of Weick's scale. It is a recurrent concept in the HMI literature, where a lot of attention is devoted to the derived challenges. Dorton and Thirey (2017) present a notion, effective variety, and an interesting model to analyze characteristics of HMI for providing the right level of complexity to the operator to achieve optimal decision making and avoiding situation awareness degradation. The work is based on the theory of Requisite Variety (Ashby, 1958). Balancing variety and complexity is also discussed by Dahlberg (2015), even though at a more general level, not referring directly to HMI. The stated need for tools helping to 'imagine' solutions indicates how HMI should support the operators in critical conditions. Carrol (2015) discusses further the role of ambiguity and the need for multiple perspectives and innovative solutions to reduce ambiguity.

Flach (2017) emphasizes the challenge for HMI to be as much as possible compatible with cognitive processes leading to 'innovative thinking' and "productive thinking".

Rankin et al. (2016) discuss the difficulties for the operators to keep up with technology and how it can interfere with the re-framing activity (Klein, 2006) following a surprising event. Their goal was to analyze reframing activity in a cockpit and the challenges for achieving this, like to recognize and construct a frame, elaborate it, question it and change it. HMI is at the core of some of these challenges, including absence of salient cues, detecting subtle cues, and conflicting data. These challenges may lead to too narrow interpretations missing the real cause, coping with insufficient system knowledge, multiple goals and trade-offs, and coping with uncertainties. Reframing is also considered by Landman (2017), pointing out how complex and unclear interfaces can hinder sensemaking. Malakis and Kontogiannis (2012) look at reframing too, suggesting utilising the cognitive system engineering paradigm in designing support system and HMI.

Higher levels of automation in I&C (Instrumentation and Control) systems may provide more 'confirmed cues'. This may lead operators to over-trust the system. Somehow, in these situations equivocal cues may be useful to get a better understanding of the situation, to get a larger breadth of the situation presented.

3.2.2 *Social*

Sensemaking is a *social* activity in that plausible stories are preserved, retained or shared. In Weick's (2009) definition, the social dimension ranges from social to solitary resources for sensemaking. This aspect is based on a network of communication channels through which human actors share their interpretations. The traditional social dimension of sensemaking is heavily treated in the literature, also in process control, e.g., on the topic of crisis management by Le Bot et al. (2018). When it comes to the link between the social dimension of sensemaking and HMI, we did not find many direct hits in the literature search. However, there is a huge amount of literature about HMI and teamwork. Braarud et al. (2015), in proposing a new method for evaluation of human performance, consider dimensions such as teamwork and how this is influenced by HMI.

Computer systems could be considered agents in the sensemaking process. Van Diggelen et al. (2018), van de Broek et al. (2017) and Vilim et al. (2015) all propose and explain decision support systems that suggest diagnoses and interventions or predicting evolution of a situation. In this case machines can be viewed as agents with their own characteristics. Automatic text, document analysis can be an additional tool providing new insights over recorded stories.

3.2.3 *Plausibility*

The plausibility dimension discusses actions in the presence of incomplete information and uncertainty. Expertise and knowledge of the principles governing the controlled process, in a thread of reasoning typical of humans, fill the 'gaps' and to formulate a scenario guiding the action.

Methods for Human Reliability Analysis (HRA) are used in the nuclear and oil industries to evaluate the human performance in safety critical tasks and its plausible impact on the safety of the plant. HRA methods are beneficial in evaluating the effects of HMI on operator's performance, but most of them are not developed for digital interfaces (Boring, 2014). A similar conclusion is stated by Porthin et al. (2016), a literature review for Human Reliability Analysis methods for digital human system interfaces.

Availability of big data can provide valuable input but on the other hand leaving the machine to analyze the huge amount of data unsupervised creates the risk of spurious correlations (Calude, et al. 2017). Operators need to evaluate the found patterns by deep understanding based on their expertise to give relevance and meaning to them. Culen (2014) discusses how visual immediacy can be a powerful concept to facilitate reasoning. Favaro and Saleh (2018) are using temporal logic to dynamically support real time operator's awareness providing warning signs about approaching hazardous situations. In Groen et al. (2016), the probabilistic reasoning is taken into consideration to combine information from human and artificial agents.

3.2.4 *Enactment*

Action is one of the key elements characterizing sensemaking as a very dynamic process interleaved and responding to a dynamic environment. A large spectrum of activities is considered, from information gathering, analysis, to intervention on the controlled process.

In sensemaking the agent is the human, however, in modern control centers the automated system is an integral part of action. In a digitalized world automation is taking care of implementing higher-level commands from operators for more and more components and sub-systems. It may be challenging for the humans to understand the behavior of new automation.
As the maritime sector is moving toward a full automation of ships, as pointed out in (Van den Broek and al. 2017) a joint human automation framework should adapt to a collaboration style depending on the situation. A mixed-control approach is pursued to give the operators the possibility to resume the control effectively with the help of intelligent operator support systems.
Other examples of advanced systems for decision support in control centers are discussed by (Vilim et al. 2015; Van Diggelen et al 2018).

Collaboration and issues of authority, responsibility, over-trust in adaptive automation framework are discussed in Inagaki (2010). Here the joint cognitive system approach is advised for realizing human technology co-agency.
The joint cognitive system perspective is also the framework of choice in Howard (2012), discussing the intentional awareness construct for improving the coupling between an agent and the associated system performing a task. Here the information is presented with its context and its intent, adding causal and temporal dimension to the relevant situational information.

The System Theoretic Process Analysis (STPA), presented for example in Mahajan et al (2017), is a hazard analysis method putting attention on the interaction among components, human or artificial, of the system.

Ecological Interface Design (EID) is a framework for guiding the design of advanced user interfaces for complex socio-technical systems. An interesting analysis of concerns and misconceptions of EID in Borst et al. 2015 touches upon the many aspects of sensemaking.

3.2.5 *Retrospection*

Of the seven elements characterizing sense-making this is probably the most debated. Rosness et al. (2015), during observations in an operating theatre, identified a relevant role of prospective sensemaking. The actors gained a common understanding of the situation based on what happened and their actions, to arrive to a better decision. In addition, the actors produced possible relevant patterns to monitor and detect in the near future, achieving a proactive behavior.
Pazouki et al. (2018) look at the maritime sector with an increasing level of automation. They analyze the operator SA in situations when the autopilot fails. They observed delays in recognizing the failure situation and point to the need for proactive monitoring principles to bring into HMI design, for helping the operators to build an accurate mental model. They also suggest a closer link between HMI and training.

3.2.6 *Ongoing*

Sensemaking is a dynamic, continuous process allowing to follow the changing environment. We have mentioned that sensemaking is triggered in certain situations. Probably a more accurate description is that sensemaking is always an active process, at different levels of intensity. There is a time-line at the basis of understanding a dynamic landscape on which facts, actions, interpretations, information and narratives are anchored. Attention of the operators moves along this time line. Digitalization can perturbate this. E.g., as considered by Giraudet et al. (2015) dealing with information via auditory signals can be detrimental in situations of stress and pressure in high risk decision making. HMI design is a critical element for avoiding introduction of additional tasks.

3.2.7 *Identity*

This dimension discusses whether there is a defined or vague identity notion. This aspect seems to have less relation to digitalization as long as roles are not disrupted by new processes. Multiplicity of identities involved is a resource, providing the variety of competences required.

Including machines as agents in the sensemaking process can raise issues on how well the automatic system can be recognized as such. This is in turn related to the transparency of the system (Borst et al, 2015), how the system is able to make manifest its own activity (the goal pursued, the situation detected, the action carried out), in a suitable way for the human to easily understand. A related approach is making the automation knowing more about the cognitive load of the operator, as for example presented in Liu et al. (2016).

4. Summary and conclusions

HMIs have a key role in supporting the operators in safety-critical situations, and the aim was to investigate this to lay the basis for how to design HMIs in the future maritime context.

A direct search combining sensemaking, HMI, and safety-critical situation gave limited results. We believe this is due to a different usage of the terms in different disciplines. The concept sense-making is mainly developed in organizational sciences, while for example the related term Situation Awareness (Endsley, 1995) is more known in the Human Factors and process control field. Thus, designing HMI for sensemaking will include many of the aspects of designing for optimal SA.

In order to link the literature on sensemaking with HMIs and process control, we then discussed the found literature according to the seven dimensions of sensemaking by Weick (1995 and 2009). The dimensions of Weick were found useful in the discussion. The links to HMI were very direct for Cues, which is a main trait of the HMI. The relation between the HMI and the Social dimension can be viewed as how teamwork is mediated by the HMI. However, most of the existing literature on sensemaking does not make this link to HMI. The other dimensions show a more indirect link. Enactment and retrospection open the way to the vast theme of collaboration between human and automation. One of the most rapidly developing sectors in this respect is represented by autonomous cars. Analogies in sense making from this field to the maritime field can be drawn, especially within Dynamic Positioning, regarding the dynamics of the environment and the goal. Several other interesting analogies can also be drawn from the monitoring activity performed in a control room of a nuclear power plant, where sensemaking can shift dramatically and quickly from periods of monotony to critical situations.

The literature review shows the key role HMI plays in sensemaking in safety-critical situations in high-risk industries, suggesting that almost all dimensions should be considered in designing and realizing a supporting HMI. Recent developments in Human Reliability Analysis on the effects of digitalized control room on crew performance should also be taken into account

Based on the characteristics of HMI for sensemaking identified in this paper, the project will investigate prototypes to reach a conclusion on the most central characteristics of HMIs to support sensemaking.

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