Sensemaking in Critical Situations and in Relation to Resilience—A Review

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Accidents and incidents, such as the capsizing of the anchor handling vessel Bourbon Dolphin in 2007 and the unintended list of the drilling rig Scarabeo 8 in 2012, underline the need for addressing sensemaking in safety-critical situations in the maritime domain to reduce risks. Sensemaking and risks must be understood as a part of the organizational context of the incidents. This paper presents the results of a comprehensive qualitative literature review conducted to establish more knowledge on sensemaking in the context of safety-critical situations and on the relation between the concepts of sensemaking and resilience. In the obtained literature sensemaking is used as a frame of reference for understanding accidents; it is used in relation to critical situations or complex operations in general; it is described by some as a process creating situational awareness; and it is explained by others mainly in terms of how it relates to resilience. Sensemaking creates the context for being resilient; at the same time sources of resilience help to make sense of the situation. Few authors provide explicit characteristics of sensemaking in safety-critical situations, where discrepancies can be supported by redundant systems or by training to ensure the needed questioning attitude. There is a lack of literature regarding sensemaking in safety-critical situations and in relation to resilience that also addresses important aspects of training and system design. [DOI: 10.1115/1.4044789]

1 Introduction

The paper is divided into five sections. Section 1 provides motivation, research question, and definitions. Section 2 provides a description of the methodology. Findings from the review are presented in Sec. 3 and discussed in Sec. 4. Finally, Sec. 5 provides the conclusion and some thoughts about further research.

1.1 Motivation and Purpose. In 2012, the Scarabeo 8 semi-submersible drilling rig had an unintended list of 7 deg during drilling. The triggering cause was a misunderstanding (i.e., poor sensemaking) in the handling of the ballast system. The investigation report attributed the incident to weaknesses in the control room's human-machine interface (HMI) and insufficient training of control room personnel. This example illustrates that sensemaking based on Information and Communication Technology (ICT)-based control systems is key to controlling major accident risk both in the maritime and offshore industries, and that operators' sensemaking based on information from these systems is a key factor in avoiding major accidents and enabling recovery in near misses. The ability to handle demanding maritime operations safely is increasingly dependent on ICT-based control systems (such as dynamic positioning and ballasting). Such systems play a crucial role in the handling of critical situations by presenting safety-critical information that allows operators to make sense of the situation. The growing dependence on such systems changes need for design of systems, work processes, competence requirements, and above all, it introduces new opportunities and challenges related to the handling of risk in demanding maritime operations. The risk of maritime accidents has increased—frequencies related to the occurrence of serious accidents show increased values of about 30% from 2000 to 2012 [1]; thus, we need to explore the background of sensemaking in order to understand how to reduce risks in this complex setting.

The term sensemaking refers to the way actors extract information from their environment and interpret and act on this basis; in short "making sense of the situation." This process involves tight interactions between humans and technology that places high demands on the quality of the technology interface, organizational issues (e.g., responsibilities, manning, and procedures), and the experience and the training of the operator. We therefore hold that sensemaking is an important taxonomy in a world of increasing autonomy and complexity. Sensemaking is chosen as strategic concept since human sensemaking is dependent on human factors issues, organizational issues, and the quality of the technology, i.e., the whole sociotechnical system, to create understanding. Arguing, like [2], that human error is a symptom of problems with the system, being an effect rather than a cause, we hold that exploring the sensemaking process may help to avoid the fallacy of "human error," i.e., blaming humans for working in unsuitable conditions. Sensemaking supports the idea that humans and their actions are dependent on the whole socio-technical system. This broad perspective was highlighted in the U.S. chemical safety and hazard investigation board report following the Macondo well blowout in 2010, illustrating a gap in U.S. offshore regulation and guidance to incorporate more robust management of human factors. The report highlights the importance of human factors engineering for safety critical system design and usage. It also stresses the need for development and use of nontechnical skills, including communication, teamwork, and decision-making [3].

Research literature also shows that crises and accidents are often characterized by ambiguity of cause, effects, and means of resolution; thus, they provide powerful arenas for sensemaking [4]. Sensemaking as it unfolds during accidents has been research in several contexts including mining disasters [5], climbing disasters [6], an air-force friendly fire accident [7], space shuttle accidents [8,9], maritime accidents [10], as well as the Bhopal accident [11,12], the Tenerife air crash [13], and the Mann Gulch fire [14].

1.2 Research Questions. This literature review was conducted as part of a research project on sensemaking in safety-critical situations within the maritime domain. Safety-critical situations denote situations or operations that, if they go wrong, have a large potential for causing harm to people, property, or environment. This review is

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not specific to maritime operations. Figure 1 illustrates the central role of the sensemaking process in critical situations. It also illustrates the importance of design of safety-critical systems and the training to facilitate sensemaking. Finally, it highlights that none of these processes can be understood in isolation from the more general human, technological, and organizational context of which they are part.

There is a wide range of situational factors that can influence sensemaking, such as context, language, identity, cognitive frameworks, emotion, politics, and technology [15]. In the context of a safety-critical situation, one might expect characteristics of sensemaking other than or more prominent than the characteristics of "everyday sensemaking," such as strong negative emotions like stress and fear.

The sensemaking processes in an organization provide meaning to an event or situation in a given context. In such situations, sensemaking can be a source of resilience, in that it enables a person or a crew to "bounce back" when put under stress. The central sensemaking publication [16], states that literature on sensemaking and resilience are closely related as both focus on how managers deal with ambiguity and extreme shocks in the environment.

As a basis for further research, this paper describes the findings from a qualitative literature review aiming to answer the following two research questions:

(1) How does the literature use the term sensemaking in the context of critical situations?
(2) How does the literature describe the interconnections between the concepts of sensemaking and resilience?

The increasing dependency on ICT-based control systems has made the impact of system design on sensemaking an important topic in our project. In order to understand and improve the handling of safety-critical control systems, there is a need to address both the design of systems and the training that enables operators to deal with the unexpected. Hence, it was also noted whether the obtained literature address sensemaking in relation to training or system design.

1.3 Definitions of Central Concepts

1.3.1 Sensemaking. Sensemaking started to emerge as a concept in organizational literature in the late 1960s [17] but was made prominent almost three decades later with Karl E. Weick's seminal book about sensemaking in organizations [18]. The book presents seven interrelated properties, stating that sensemaking is grounded identity construction, retrospective, enactive of sensible environments, social, ongoing, focused on and extracted by cues, and driven by plausibility rather than accuracy. The concept has since been the subject of considerable research and has assumed an extensive variety in definitions and significances. Rooted in recurrent themes from a comprehensive literature review, [17] developed the following definition:

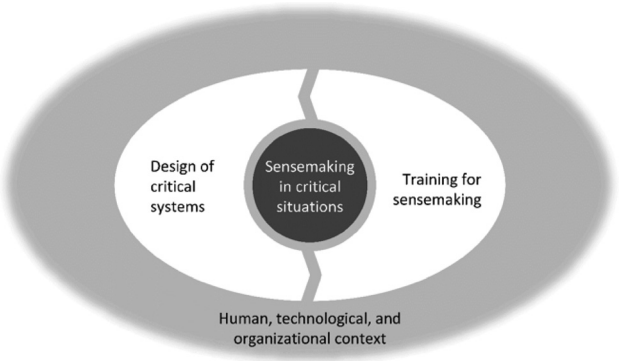

Fig. 1 Areas of focus to support sensemaking in critical situations

> *"[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" (p. 67).*

Sensemaking can thus be described as consisting of three interrelated processes: creation, interpretation, and enactment. For issues, events or situations to become triggers for sensemaking, there must be a discrepancy between expectations and reality, either in form of an unexpected event or the nonoccurrence of an expected event. There are many factors that influence whether violated expectations or cues trigger sensemaking, e.g., individual or organizational identity, cognitive frames, personal or strategic goals, and technology [15–17].

Sensemaking does not take place in isolation but in a specific context [15]. The immediate action context influences how actors notice and extract cues from the environment and how these cues are interpreted. The immediate social context is important as individuals interpret their environment in and through interactions with others; thus, constructing accounts that allow them to comprehend the world and act collectively [19]. Also, the broader institutional context, including history, culture, epistemics, and industry, influences the sensemaking process and its outcome [15].

According to the "data/frame theory" [20], the sensemaking process is based on an initial framework. A frame functions as a hypothesis about the connections among data; it defines, connects and filter data. As we acquire more data the frame is questioned, data may be added to elaborate a frame or data may be explained away to restore the frame. Alternatively, questioning the frame may lead to reframing where the initial frame is rejected and replaced by a more accurate one.

1.3.2 Resilience. Resilience is most frequently described in terms of successful adaptation in coping with adversity. Arguing that safety management should move from ensuring that "as few things as possible go wrong" to ensuring that "as many things as possible go right," [21] call this perspective safety-II. It differs from safety-I in that it focuses on a system's ability to function under varying conditions, making the number of intended and acceptable outcomes as high as possible. Thus, safety-II pertains to resilience.

From the perspective of resilience engineering, performance variability is not a threat that should be avoided; in complex socio-technical systems, variability is considered normal and necessary. According to Ref. [22], resilience is defined as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" (p. 275). Ibid define four corner-stones of resilient systems, the abilities to (1) respond to events, (2) monitor on-going developments, (3) anticipate future threats and opportunities, and (4) learn from past failures and successes alike.

2 Methodology

A literature search was conducted to find literature addressing (1) sensemaking in the context of safety-critical situations and (2) the interconnection between sensemaking and resilience, where both terms were used. Literature was obtained through Boolean searches of the following interdisciplinary databases of scientific publications: Scopus, Web of Science, Google Scholar, and Oria. Based on the objective of the study, the keywords *sensemaking*, *resilience,* and *safety-critical* were selected. To capture variations in these keywords, more specific search terms were used. These are listed in Table 1.

Different combinations of the terms in Table 1 were used due to different possible search approaches in the various databases. Broad search terms (e.g., "high-risk") were used when searching the abstract databases, scopus, and web of science, whereas

Table 1 Included search terms

Keyword	Search terms
Sensemaking	Sensemaking; sense-making; sense making
Resilience	Resilience; resiliency; resilient
Safety-critical	Safety-critical; safety-critical situation(s); safety-critical operation(s); safety critical; safety critical situation(s); safety critical operation(s); high-risk; high-risk situation(s); high-risk operations(s); high risk; high risk situation(s); high risk operation(s); hazardous; hazardous situation(s); hazardous operation(s)

searches in google scholar and oria were conducted using more specific terms (e.g., "high-risk situation"). To avoid an excessive amount of search results, general searches in google scholar included variations of all three keywords of sensemaking, resilience, and safety-critical. When searching the abstract databases and when using the "all in title" function in google scholar, search terms related to two of the three keywords were used. Our findings should be considered in light of the limitation in the search terms. For instance, in addition to the search terms related to the keyword *safety-critical*, we could have included additional terms such as surprising and emergency.

To be included for further review, the publications either had to be relevant for understanding sensemaking in the context of safety-critical situations or draw on the relationship between sensemaking and resilience. We did not include books in this literature review, and a few papers were excluded as we requested, but did not receive the full text.

3 Findings From the Review

The literature search resulted in 40 documents that were included in the review (see Table 2 for a chronological list of the publications). The reviewed literature includes 33 articles published in peer-reviewed scientific journals, four papers presented at international conferences, workshops, or symposiums, one licentiate's thesis and two Ph.D. thesis.

No inclusion criteria were applied regarding publication year; however, the results show that the use of the term sensemaking in the context of safety-critical situations, or in relation to resilience, is relatively recent. All but three of the publications were published during the last decade (2009–2018).

The following subsections present the findings from the literature review. First, a presentation of how the publications define sensemaking is provided. Second, a description of the use of sensemaking in the context of critical situations is presented. Third, findings regarding the interconnection between sensemaking and resilience are described. Finally, a subsection is included describing to what degree the included literature addresses aspects of system design and training that enhances sensemaking.

3.1 Applied Definitions of "Sensemaking". As previously outlined, the concept of sensemaking does not have one single, agreed-upon definition. According to Ref. [17], the term is often used without any associated definition from the literature, and when definitions are provided, there are a variety of meanings asserted to it. These definitional challenges are also discussed in Ref. [23], stating that sensemaking is frequently quoted as a widespread notion, without a detailed description. Table 3 provides an overview of the applied definitions of sensemaking in the 40 publications that were included from the literature search.

3.2 How the Term Sensemaking Has Been Used in the Context of Critical Situations. To comprehend and understand the variety of ways in which the literature uses the term sensemaking in the context of critical situations (i.e., research question 1), the following findings are structured according to five sub categories (number of relevant publications in brackets). These are publications that:

(1) use sensemaking as a frame of reference for understanding accidents or incidents (7);
(2) use sensemaking in relation to critical and ambiguous situations in general (8);
(3) use sensemaking in relation to critical and complex operations (6);
(4) describe sensemaking as a process creating situational awareness (8); and
(5) primarily discuss sensemaking in the context of resilience and adaptation (7).

These categories are not mutually exclusive; that is, some of the publications included in category 1, 2, and 5 are also included in category 4. In total, 31 of the 40 papers in Table 2 provide input to answering research question 1.

3.2.1 Sensemaking as Frame of Reference for Understanding Accidents or Incidents. The publications that use sensemaking as a frame of reference for understanding accidents or incidents range from discussion on a societal level to examining specific accidents. By discussing how Perrow's work on normal accidents [25] has influenced research on sensemaking and ecosystems, Gephart [26] provides insight into how societies legitimate high-risk technologies that are prone to failure and to environmental disaster.

A public inquiry into a well blow-out was investigated by using computer supported textual analysis [27]. It was found that quantitative practices and terms played an important role in inquiry sensemaking; hence quantitative sensemaking is suggested as an important topic for sensemaking research and organizational behavior studies of crises.

Three of the publications describe how accidents developed due to people overlooking or explaining away cues present in their environment. In his analysis of the Mann Gulch fire disaster, Weick described how the smokejumpers' persistent expectations led to "the interrelated collapse of sensemaking and structure" [14]. They expected to find a fire that they would have control over within the next morning. This positive illusion prohibited them from making sense of the cues in their environment contradicting this expectation. Weick describes the disintegration of the group as a result of unclear roles, identity issues, and an intense emotion of panic. In the case of the Montara well blowout in 2009, it was also suggested that personnel overlooked cues from information available to them prior to the incident [28]. Based on their experience, they believed what they were doing was safe, and this belief directly influenced which cues they extracted from their environment. Also, exploring why flooding of small firms does not consistently lead to resilient adaptation of premises, Harries et al. [29] explained how business owners have a desire to protect their existing sensemaking structures and resist information that challenges these.

The literature also describes incidents in which sensemaking has been successful. The investigation of a nuclear power plant incident [30] found that the control room operators' sensemaking was successful despite of lacking relevant data and supporting technology, rules, procedures, and training. The operators practice

Table 2 Overview of publications from the literature search

Author(s)	Year	Topic
Weick	1993	Disruptions of sensemaking
Gephart	1997	Quantitative sensemaking during crises
Gephart	2004	Normal risk: Technology, sense making and environmental disasters
Back et al.	2009	Reflection in the control room during safety-critical work
Baran and Scott	2010	A grounded theory of leadership and sensemaking
Bergström	2012	Aspects of organizational resilience in escalating situations
Grøtan and Størseth	2012	Integration of organizational resilience into safety management
Hayes	2012	Operator competence and capacity in complex hazardous activities
Lundberg et al.	2012	Resilience in sensemaking and control of emergency response
Sanne	2012	Learning from adverse events in the nuclear power industry
Hutter and Kuhlicke	2013	Understanding resilience in the context of planning and institutions
Rankin	2013	Adaptive performance and resilience in high-risk work
Rantatalo	2013	Sensemaking and organizing in the policing of high-risk situations
Favarò and Saleh	2014	"Observability-in-depth" as a complement to defense-in-depth
Rankin et al.	2014	A framework for analyzing adaptations in high-risk work
Haavik	2014	The nature of sociotechnical work in safety-critical operations
Norros et al.	2014	Operators' orientations to procedure guidance in NPP process control
Saleh et al.	2014	Safety diagnosability and observability of hazards in design
Van den Heuvel et al.	2014	Police strategies for resilient decision-making and action implementation
Barton et al.	2015	Contextualized engagement in wildland firefighting
Dahlberg	2015	Exploration of resilience and complexity
Grøtan and van der Vorm	2015	Conceptual approach to operational and managerial training of resilience
Hunte et al.	2015	Dialogic sensemaking as a resource for safety and resilience
Van der Beek and Schraagen	2015	Adaptability and performance in teams to enhance resilience
Danielsson	2016	Cross-sectorial collaboration in a potentially dangerous situation
Jahn	2016	Adapting safety rules in high reliability contexts
Hardy and Costargent	2017	Improving operational resiliency and sensemaking during crisis
Hoffman and Hancock	2017	How to measure and compare resilience
Landman et al.	2017	A conceptual model for pilot's ability to deal with unexpected events
Lofquist et al.	2017	Why different subcultures interpret safety rule gaps in different ways
Siegel and Schraagen	2017	Making resilience-related knowledge explicit through team reflection
Takeda et al.	2017	Developing resilience in disaster management promoting sensemaking
Teo et al.	2017	How leaders utilize relationships to activate resilience during crisis
Danielsen	2018	Embodied sensemaking, an approach to maritime information design
Favarò and Saleh	2018	Temporal logic for safety supervisory control and hazard monitoring
Flandin et al.	2018	Improving resilience in high-risk organizations: Innovative training design
Harries et al.	2018	Small firm resilience: Sensemaking, emotions and flood risk
Hillmann et al.	2018	Educating future managers for resilient organizations: Scenario planning
Tisch and Galbreath	2018	Organizational resilience through sensemaking: extreme weather events
Van der Merwe et al.	2018	Conceptualizing and assessing the resilience of essential services

by interacting with training, technology, and procedures produced a practical competence that made them able to make sense of events, even unprecedented ones. In a study of leadership processes within extreme events, 100 reports of "near-miss" situations in which firefighters narrowly escaped injury or death was analyzed [31]. Leadership was highlighted as a collective sensemaking process, where ambiguity is reduced, and resilience promoted through interaction between leaders and followers. Central categories discussed in this paper are direction setting, knowledge, talk, role acting, role modeling, trust, situation awareness, and agility.

3.2.2 Sensemaking in Relation to Critical and Ambiguous Situations in General. This section summarizes the publications that use sensemaking in relation to critical and ambiguous situations in general, based on research in several different contexts.

In a Ph.D. thesis exploring sensemaking and organizing in the policing of high-risk situations, Rantatalo [32] examined how leadership, management, and ICT system impact organizational reliability and sensemaking. The author describes how interface design of communicative systems scaffold and frame possible actions and that sense-giving in terms of goals, directions, and allowance of autonomy were found to be desirable strategies of leadership. How leadership facilitates sensemaking was also studied by Barton et al. [33]. Based on interviews with wildland firefighters, it is argued that actively looking for and working to understand anomalies together with proactive leader sensemaking play a crucial role in successful organizational performance.

In Ref. [34], it is described how established understandings, routines, and roles may impose an "invisible hand" on sensemaking in control room environments and suggest that people should be provided with the opportunity to reflect on experience during safety-critical work and that technology should be designed to support the reflective capacity of people.

Favarò and Saleh [35] propose a safety principle called "observability-in-depth," characterized as technical, operational, and organizational design to enable monitoring and identification of emerging hazardous conditions. In a later paper [36], the same authors extend the framework for safety supervisory control with temporal logic to improve accident prevention and dynamic risk assessment. They hold that, when applied on-line, it provides

Table 3 Applied definitions of "sensemaking"

Applied definitions of sensemaking	No. of publ.	Ref. ID
Using sensemaking as a general notion without providing any associated definition.	5	[30,35,36,46,47]
Providing references to the work of others, but without reproducing the actual definition of the work they refer to	5	[33,41,53,58,59]
Weick's reanalysis of sensemaking as a generic phenomenon; "… the basic idea of sensemaking is that reality is an ongoing accomplishment that emerges from efforts to create order and make retrospective sense of what occurs" (p. 635).	1	[14]
Referring mainly to Weick's works on sensemaking	10	[27,28,31,34,39,44,45,49,54,61]
Defines sensemaking as "the process of reflecting on experience and interpreting the meaning of events" (p. 23).	1	[26]
Providing more detailed and extended descriptions/reviews of sensemaking referring to Weick among several others.	11	[23,29,32,40,42,50,51,55,57,60]
Referring to Klein's "Data/Frame Theory" of sensemaking, e.g., [19]	2	[62,66]
Referring to the work of both Weick and Klein	3	[37,43,52]
Definition based on the Cynefin sensemaking framework, distinguishing between knowable/known domains and complex/chaotic domains as described in Ref. [24]	2	[63,64]

warning signs to support the sensemaking of emerging hazardous situations and identifying adverse conditions that are close to being released.

Two publications emphasize the importance of training to support sensemaking in critical situations. Based on reviewed literature on surprise, startle, resilience, and decision-making, Landman [37] propose a conceptual model for explaining pilot performance in surprising and startling situations. It is argued that sensemaking processes are especially vulnerable to issues caused by startle or acute stress and that variable and unpredictable training can improve frame supply and frame adaptation skills. Reference is made to Kahneman [38], describing sensemaking as an explorative process that is active, analytical, conscious, and potentially effortful, characterized by top-down or goal-directed processing. In Ref. [39], an experiment was carried out to examine how personnel from three different organizations, two from the emergency services, and one from the elderly care center create meaning and intend to act in a potentially dangerous situation. The author argues that cross-sectorial training is important for the ability to interact with and make use of other profession's knowledge and thoughts in crisis situations.

A Ph.D. thesis focusing on explorative studies of high-risk situations [40] argues that the organizational science community has so readily embraced the sensemaking model because it offers co-existence of explanation and interpretation, a classic conflict of the social sciences.

3.2.3 Sensemaking in Relation to Complex and Critical Operations. Some of the included literature is not related to critical situations directly but rather to aspects that may be prone to safety-critical events. Among these are Lofquist et al. and Jahn [41,42], both of which discuss sensemaking in relation to safety rules in high-risk environments in which individuals may be subject to emerging, ambiguous settings. Another study uses the theoretical perspective of orientations in a study about nuclear power plant operator's basic assumptions about the role of operating procedures in action [43]. Here, orientation is described as an epistemic attitude to work that influences the process and content of sensemaking in situations that require action. Operator behavior is regulated by conceptions in the organization about the work and how balance between autonomy and guidance is found.

Haavik [44] introduces *sensework* as a type of *sociotechnical* work in safety-critical operations as it unfolds in settings that are characterized by multidisciplinary interpretative work in high-tech environments, where direct access to the phenomena of interest is restricted and the dependence on sensor data and model support is high. Sensework is related to (but not the same) as the concept of sensemaking in Weick's terms.

A recent literature review argues that the research strand on embodied sensemaking is relevant for the maritime sector and that embodied sensemaking is congruent with the term ship sense. Ship sense is described as a form of tacit knowledge regarding the maneuvering of a ship [45].

Saleh et al. [46] point out that risk safety literature has drifted toward the organizational and social sciences or the refinement of probabilistic modeling on the other side. One important aspect that has faded is the engineering and design side of system safety, supporting the sensemaking process of the operator. Ibid uses the safety-diagnosable principle, which is a requirement that all safety-degrading events or states must be observable or diagnosable for operators, arguing that the principle provides one way of improving operators' sensemaking and situational awareness.

3.2.4 Sensemaking as a Process Creating Situational Awareness. One of the papers is structured around the concepts of sensemaking, situational awareness, and resilience [23]. It intends to show how the three concepts are interconnected and tries to create an understanding of their mutual influences in the construction of organizational performance in times of crisis. With reference to Ref. [47], sensemaking is described as the transition from levels 1 to 2 situation awareness through effortful processes of collecting and synthesizing information, by story building, and mental models.

In Ref. [48], a simulated hostage negotiation setting is used to demonstrate how a team of strategic police officers can utilize specific coping strategies to minimize uncertainty at different stages of their decision-making in order to foster resilient decision-making to effectively manage a high-risk critical incident. The paper argues that decision-makers must attempt to achieve situation awareness, which results from the process of sensemaking.

Several other publications in this review briefly draw on the relationship between sensemaking and situation awareness, mainly arguing that sensemaking is an important aspect of situational awareness or that situational awareness is an outcome of sensemaking [35,36,39,49]. In Ref. [31], however, situational awareness is listed as one of several aspects in a model that aims to create collective sensemaking. In Ref. [35], it is argued that the interplay between observability-in-depth, situational awareness, and sensemaking is a fruitful venue for further research.

3.2.5 Sensemaking in the Context of Resilience and Adaptation. Quite a few of the publications primarily focus on resilience and adaptability in critical and ambiguous situations. Some propose models for describing or analyzing resilience or adaptive behavior [49–51], or principles for training to enhance resilience

[52]. Others discuss the importance of resilience related to disaster management [53], high risk work [54], scenario planning in strategic management education [55], and extreme weather events [52]. All these publications use sensemaking as a concept closely related to that of resilience, often describing it in terms of this relationship. Findings regarding the interconnections between the two theoretical perspectives of sensemaking and resilience are presented in the following Sec. 3.3.

3.3 Interconnections Between Sensemaking and Resilience. To comprehend the variety of ways in which the literature describes the interconnections between sensemaking and resilience (i.e., research question 2), the findings are structured according to three sub categories (number of relevant publications in brackets). These are publications that:

(1) describe resilience as a factor that enhances sensemaking (1);
(2) describe sensemaking as a factor that creates or influences resilience (14); and
(3) describe sensemaking to analyze or explain resilience (11).

In total, 26 of the 40 papers in Table 2 provide input to answering research question 2.

3.3.1 Resilience as a Factor Enhancing Sensemaking. In reanalyzing the Mann Gulch fire disaster, Weick focuses on how organizations can be made more resilient [14]. He argues that the only pattern that can maintain resilience in the face of crisis is a structure in which there is both an inverse and a direct relationship between role systems and meaning. Key sources of resilience that make groups less vulnerable to disruptions of sensemaking is: improvisation and bricolage, virtual role systems, the attitude of wisdom, and norms of respectful interaction.

3.3.2 Sensemaking as a Factor Creating or Influencing Resilience. Most authors argue that sensemaking is an important source for achieving organizational resilience. These publications typically describe sensemaking as a capability essential for creating a resilient organization [55], that sensemaking contributes to resilience through strategies for resilient decision-making [48], or that there are certain qualities of sensemaking and organizing processes that vouch for safety and resilience [42]. A more recent article concludes that both sensemaking and situational awareness are required conditions for an operational resilience [23]. In Ref. [43], the authors link sensemaking to what they call the interpretative orientation, recommending that appropriation of interpretative orientation should be actively supported as a means to facilitate resilience. According to Ref. [54], sensemaking is central for the ability to control a process and adapt in an appropriate manner. Thus, sensemaking is important in adaptability, which in turn is essential for being resilient. The author also draws lines between Hollnagel's four central abilities to characterize a resilient system and the sensemaking capabilities of seeking information, ascribing meaning and action.

The significance of leadership is emphasized in Ref. [31], which argues that leaders play a critical role in creating and maintaining a context for actively managing uncertainty that likely underlie organizational resilience. Collective or shared sensemaking is described to facilitate resilience in Refs. [56] and [57], while Baran and Scott [31] argue that leadership is a collective sensemaking process in which ambiguity is reduced and resilience promoted.

In Ref. [58], the authors present a program for training for operational resilience capabilities, emphasizing that training elements should be aimed at sensemaking. Flandin et al. [59] argue the design of innovative training situations that are likely to improve individual, collective, and organizational resilience should support participatory-sensemaking and collective sensemaking.

At the community level, Tisch and Galbreath [52] studied organizational resilience to the impact of climatic changes. By introducing the term "community sense-giving," the authors illuminate how sensemaking occurs in communities, arguing that sensemaking both enables and constrains resilience. Takeda et al. [53] highlight the importance of resilience in the disaster management process. Through a review of disaster management literature, along with illustrative examples from global disasters, they emphasize the need to focus on the development of sensemaking and heedful interrelating by the local agents who are likely to be present in disasters.

3.3.3 Sensemaking as a Means to Analyze or Explain Resilience. Several authors use sensemaking to analyze or explain resilience by theoretical frameworks or models. According to Ref. [40], the development of a theoretical framework for analyzing organizational resilience in escalating situations must relate to the explanatory potential of sensemaking theory. Arguing that collective sensemaking in crucial for resilience, another framework identifies four key domains that require investment to build resilience of essential services that are produced by complex adaptive sociotechnical systems [60].

To understand how groups, organizations, and networks make sense of resilience in the context of a crisis, Hutter and Kuhlicke [61] argue that one should consider the four processes of committing to resilience, expecting resilience, arguing about resilience and manipulating with resilience. These are referred to as sensemaking processes.

The authors of Ref. [51] present a framework for analyzing adaptations in high-risk work. Here, they explain how sensemaking is important for adaptive behavior, which in turn is a prerequisite for resilience. They focus on the importance of observing sharp-end adaptations as critical to identify system brittleness and resilience.

Through a study of resilience in the context of sensemaking and control in emergency management of irregular emergencies, Lundberg [49] proposes an emergency management analysis model, called the resilient sensemaking and variety control model. It unifies and complements existing models by modeling changes in the ongoing events processes, the actors' sensemaking and control functions, and the technologies used for sensemaking and control. Focusing on the three separate developments enables identifying resilience in the choice of control functions and technologies in response to foreseen and actual process changes, their consequences, and new disturbances. Another model, called the relational activation of resilience model, explains how leaders can utilize relationships to activate resilience during crises. In this model, sensemaking plays an important role in accomplishing tasks that facilitates organizational resilience [50].

In an article on team reflection [62], the authors use reflection and the data-frame theory of sensemaking to show the relationship between knowledge and resilience, listing sensemaking, or situation assessment as one of several team resilience abilities. The Cynefin framework, used as a sensemaking device, may be an effective lens to view and understand the concept of resilience [63].

Harries et al. [29] apply the sensemaking framework to flood risk, seeking to understand how small business owners' experiences of flooding do not consistently lead to resilient adaptation.

Focusing on integrated safety management based on organizational resilience, Grøtan and Størseth [64] address issues related to complexity, sensemaking, and emergence. They refer to what Hutter and Power [65] denote the organizational encounter with risk and argue that this concept "provides a sensemaking basis for taking into account that notions clearly related to compliance as a strategy, are boundary conditions for the exertion of resilience management" (p. 1738).

Hoffman and Hancock [66] aim to promote a discussion on how to measure resilience. It explains how sensemaking provides information to the work system about whether and when the system needs to change its understanding of problem situations, and further argues that this means "adaptive and resilient sensemaking

requires mechanisms for recognizing anomalies and situations that mandate change" (p. 571).

3.4 Training and System Design Facilitating Processes of Sensemaking. Accident reports have shown that insufficient training and poor system design may impair sensemaking processes and thus lead to incidents and accidents. After the incident at Scarabeo 8, the investigation report attributed the incident to insufficient training of control room personnel and weaknesses in the control room's HMI [67]. HMI is a key factor shaping operator performance, via concepts like sensemaking and situation awareness [68]. This section summarizes findings related to aspects of training and system design to facilitate sensemaking in critical situations.

3.4.1 Aspects of Training. The accident investigation that is analyzed in Ref. [30] points to deficiencies in training. Not many of the reviewed publications propose ways of training to improve sensemaking explicitly. However, Lofquist et al. [41] focus on building capacity for individual actors to interrelate in a heedful manner. Rantatalo [32] describes how observations that were carried out were targeted joint police management training in the setting of full-scale simulated scenario, arguing that "from sensemaking and organizational reliability perspectives, high-strain situations like that described above offer a possibility to observe interaction patterns during incident management in a realistic setting" (p. 55).

One of the conclusions drawn in Ref. [37] is that interventions should focus on increasing pilot reframing skills, for instance, using unpredictability in training scenarios. The authors propose a conceptual model for explaining pilot performance in surprising and startling situations: a model that can be used to design experiments and training simulations.

A team's ability to take on flexible roles is critical for making sense of ambiguous situations. Three suggestions for improving the ability to support flexible roles are proposed in Ref. [39], one of which involves training to take on the responsibility for tasks and role outside one's professional area of specialization.

In another paper, it is stated that experiments can provide professionals from different organizations knowledge of how other professionals perceive a situation and intend to act. Thus, it is an efficient tool for training personnel in cross-sector collaboration [39].

Saleh et al. [46] mention that the ability to diagnose hazardous states provides one way to improve operators' sensemaking and situational awareness after an adverse event. It is synergetic with organizational factors in support of accident prevention, particularly safety training, which can be shaped by including off-nominal conditions.

Several of the remaining publications in this review discuss training that is aimed at enhancing resilience [40,48,57,59,64], which is an important feature in dealing with safety-critical situations.

3.4.2 Aspects of System Design. The evolution of HMIs has historically been mainly technology-driven. However, increased understanding of human psychology has transformed the principles behind design and quality criteria for such interfaces. Today, it is accepted that good HMIs cannot be designed without a deep understanding of both the task and the context in which it operates [69]. Sensemaking has often been limited to an organizational context, seldom discussing issues such as system design. In Ref. [46], it is pointed out that safety science seems to have drifted from the engineering and design side of system safety toward organizational and social sciences or refinement of probabilistic models; thus, there is a need to focus more on design and design principles to be able to diagnose hazardous states in operations; they propose a general safety–diagnosability principle for supporting accident prevention. Others argue that there are many interaction designs that aim to support problem-solving, but very few that support self-reflection and group reflection [34]. "Traditional paradigms for safety-critical systems have focused on ensuring the functional correctness of designs, minimizing the time to complete tasks, etc. Work in the area of user experience design may be of increasing relevance when generating artifacts that aim to encourage reflection." [34].

The study in Ref. [37] discusses how inappropriate responses by pilots often can be traced back to surprise, which indicates that there has been a mismatch between what is being perceived and the active mental frame of the pilot. Such inappropriate responses can be exacerbated by startle, acute stress, fatigue, or unclear and complex interface designs. If the mismatch remains unnoticed or incorrectly interpreted, it may lead to a loss of situation awareness. The authors suggest using transparent interface designs, tested in surprising situations, to aid in framing or reframing.

Gephart [26] reproduces some of the arguments in Perrow's work on normal accidents, arguing that designs are often created to meet the criteria of the "wrong" stake holders, such as managers, whose beliefs may be inconsistent with those of the actual operators using the system daily. This can result in equipment being difficult to operate and prone to accidents because of design flaws. A brief discussion on interactions between humans and systems is also made in Ref. [63]. Analyzing the investigation of a nuclear power incident, Sanne [30] explains how instrumentation in the control room was misleading due to deficiencies in the HMI.

A recent paper on sensemaking in the maritime sector argues that human sensemaking will need to be considered also in the case of autonomous ships. That is, humans will design, construct, install, test, verify, and perform maintenance within the autonomous system, and will also be present in onshore control centers [45].

4 Discussion

The current literature review aimed at describing how the selected literature uses the term sensemaking in the context of safety-critical situations and how it describes the relationship between sensemaking and resilience. The results indicate that there has been a recent increase in the number of publications discussing sensemaking under these circumstances. More than 90% of the publications obtained from the literature search were published in the last decade and close to 70% within the last five-year period. It is also interesting to note that more than 80% of the obtained literature are scientific journal articles.

However, the findings do not provide unambiguous answers to the topics of interest. This section provides a discussion on the characteristics of sensemaking in safety-critical situations, the interconnection of sensemaking and resilience, and the importance of training and design of critical systems.

4.1 Sensemaking in the Context of Critical Situations. The findings reflect that there is a great variability in definitions of the sensemaking concept, which may also explain the differences in use of the term. In the context of a safety-critical situation, one might expect characteristics of sensemaking other than or more prominent than the characteristics of everyday sensemaking. However, the findings show that few of the publications in this review discuss such characteristics explicitly, i.e., they do not explain how it differs from "everyday" sensemaking. One that do is Landman et al. [37], stating that sensemaking is characterized by top-down or goal-directed processing, referring to Ref. [38].

The resilient sensemaking and variety control model proposed in Ref. [49] are based on changes in the ongoing processes, the actors' sensemaking and control functions, and the technology used for sensemaking and control. Sensemaking variability is described as the ability to predict the tolerance of a system in the face of a disturbance, and to anticipate problems and control them before they manifest. This part of the control loop includes analyses of respectful interaction (i.e., the way people interact), wisdom

(i.e., the manner in which people relate to knowledge), and rapidity (i.e., the timeliness of understanding). These can be understood as characteristics of sensemaking.

It is also natural to mention Weick's seven interrelated properties of sensemaking stating that sensemaking is grounded identity construction, retrospective, enactive of sensible environments, social, ongoing, focused on and extracted by cues, and driven by plausibility rather than accuracy. Hardy and Costargent [23] are among the publications referring to these properties when describing sensemaking.

Some of the reviewed articles describe factors that influence sensemaking concerning safety-critical situations. The *expectations* people have may prevent them from noticing cues in their environment that contradict these expectations [13,28]. *Identity* issues and *unclear roles* contributed to the collapse of sensemaking in the Mann Gulch fire [14] and roles were also important for productive interaction and collective sensemaking in the work presented in Ref. [31]. *Emotions* like panic or startle reactions constrain sensemaking [13,37] and both positive and negative emotions impacted whether small firm owners revised their sensemaking structures [29].

Sensemaking is clearly an important theoretical framework for understanding how individuals and groups make sense of critical and ambiguous situations in which they may face hazardous consequences. Future studies making even more clear distinctions between sensemaking in critical situations and "everyday sensemaking" would constitute a positive input to the literature on sensemaking. This can be done by providing a set of characteristics or features of sensemaking in crisis.

4.2 The Interconnection Between Sensemaking and Resilience. The findings clearly acknowledge a close relationship between the theories of sensemaking and resilience. However, the direction of this relationship is not as obvious. Sensemaking creates the context for being resilient [14]; at the same time, sources of resilience, such as redundancy (i.e., redundant clues), help to make sense of the situation, i.e., [54,55]. Also, several of the included publications in this review argue that future research is needed to further understand resilience and sensemaking, i.e., [25].

As a parallel activity in the SMACS project, we have reviewed several maritime accident investigation reports. We have been especially interested in the relationship between poor sensemaking, resilience, and poor design. Like described in Ref. [14], some of the investigation reports show that sources of resilience may create understanding; or that individuals may lose understanding of the situation due to poor resilience such as poor redundancy in technical systems or organizational issues (redundancies in staffing). Redundant or alternative systems (or checking perception with other stakeholders) may reduce consequences of an unwanted situation. Looking at situations in which both sensemaking/situational awareness and resilience were impaired, we observe from five accident reports [70–74] that poor sensemaking may lead to dangerous situations and that the additional poor resilience may hinder the reduction of consequences, allowing the dangerous situation to develop into accidents.

As both the literature and accident investigations have shown, the direction of causality between sensemaking and resilience may go both ways. Several scholars have described a strong interconnection between the two concepts; hence, it is important to include aspects of both when analyzing safety-critical situations.

4.3 The Importance of System Design and Training for Sensemaking. Sensemaking is influenced by many factors, including training and the use of technology (i.e., human–machine interactions). Thus, we expected the literature in this review to address sensemaking in relation to training and system design. However, little is written on the issue of sensemaking in safety-critical situations that also concern these aspects in detail. The lack of literature discussing human-machine interfaces in sensemaking of critical situations may be due to a different usage of the terms in different disciplines [75]. Whereas sensemaking is mainly developed in organizational sciences, the term "situation awareness" is more known within the field of the Human Factors and process control. Thus, existing literature on human–machine interfaces is more often linked to that of situation awareness than sensemaking.

Discrepancies that may lead to a safety-critical situation should be supported by design, i.e., having redundant systems that can reveal discrepancies, and by training to ensure a questioning attitude. This is in line with sensemaking in high reliability organizations, where practices such as "preoccupation with failure," "reluctance to simplify," and "sensitivity to operations" support the explorations of cues and interpretations [76]. To improve safety and resilience in safety-critical operations, we must have a broad-based approach involving the socio-technical system and consider how cues and prospective sensemaking can be enabled from the design phase on.

Findings from a literature review conducted as a parallel activity in the Sensemaking in safety-critical situations (SMACS) project have identified other publications relevant for the influence of design of safety-critical systems on sensemaking [75]. Among these are Malakis and Kontogiannis [77], who discuss the utilization of the cognitive system engineering paradigm in designing support system to be effective in sensemaking. Ecological Interface Design is a framework for guiding the design of advanced user interfaces for complex socio-technical systems. The approach aims to shift the interface design from facilitating the access to data, to improving problem solving and decision-making. Since this approach looks at deeper structures of the work domain for facilitating coordination between humans and automatic systems, it is argued to be a useful for design for sensemaking.

The maritime sector is moving toward full automation of ships. Thus, a joint human-automation framework should adapt to a collaboration style depending on the situation [78]. A mixed-control approach is pursued to allow for operators to resume the control effectively with the help of intelligent operator support systems. Pazouki et al. [79] analyze the operator situation awareness in situations when the auto pilot fails and observe delays in recognizing the failure situation. The study points to need for proactive monitoring principles to bring into the design of HMIs, thus helping the operators to build an accurate mental model. It also suggests a closer link between human–machine interaction and training.

Safety-critical systems ought to support individuals and teams in making sense of critical situations. Thus, future research should aim to include the issues of system design (e.g., human-machine interactions) in examining important aspects of sensemaking. Safety-critical systems should subject to user-centered design, meaning that the design must be created to meet the beliefs and criteria of the individuals who must make the system work daily, i.e., [26]. Also, operators must be provided with relevant and enough training in using the systems, as well as in dealing with unexpected events in general.

4.4 Issues for Further Exploration. The literature review has identified several key approaches to improve sensemaking and the ability to handle safety-critical situations. Some key elements to be further explored in our future work are to increase the focus on design, collective collaboration and leadership and training—as listed in the following:

Design for sensemaking should be more in focus: Saleh et al. [46] points out that safety literature has drifted toward the organizational and social sciences or the refinement of probabilistic modeling. One important aspect that has faded is the engineering and design side of system safety, supporting the sensemaking process of the operator. Ibid uses the safety-diagnosable principle, which is a requirement that all safety-degrading events or states must be observable or diagnosable for operators, arguing that the

principle provides one way of improving operators' sensemaking. A safety principle called "observability-in-depth" is described in Ref. [35], characterized as technical, operational, and organizational design to enable monitoring and identification of emerging hazardous conditions. In Ref. [54], sensemaking is central for the ability to control a process and adapt, which is essential for being resilient; thus, adaptability will be suggested a key principle in design. Through a study of resilience in the context of sensemaking in management of irregular emergencies, Lundberg [49] propose an emergency management analysis model, called the resilient sensemaking and variety control model. It unifies and complements existing models by modeling changes in the ongoing events processes, the actors' sensemaking and control functions, and the technologies used for sensemaking and control. Focusing on the three separate developments enables identifying resilience in the choice of control functions and technologies in response to foreseen and actual process changes, their consequences, and new disturbances—and will be used in our research and development.

Collective collaboration and leadership are important issues: Based on a study of leadership in extreme events [31], the importance of leadership as a collective sensemaking process is highlighted where ambiguity is reduced, and resilience promoted through interaction between leaders and followers. In Ref. [32], the author describes how interface design of communicative systems frame possible actions and that sense-giving in terms of goals, directions, and allowance of autonomy were found to be desirable strategies of leadership—and thus subject of design activities.

Training for the unexpected and supporting adaptability and resilience: Based on reviewed literature, Landman [37] propose a model for pilot performance in surprising situations; it is argued that variable and unpredictable training can improve frame supply and frame adaptation skills, supporting sensemaking and the ability to handle surprises. The authors suggest using transparent interface designs, tested in surprising situations, to aid in framing or reframing. The importance of practice is described in Ref. [30], the operator's interaction with training, technology, and procedures produced a practical competence that made them able to make sense of events, even unprecedented ones in a nuclear power plant incident. These experiences are going to be explored further.

5 Conclusions and Further Research

The literature included in the current review found that authors either use the term sensemaking without providing a definition or there is a great variability in the definitions applied. Thus, how the notion is used in the context of safety-critical situations also varies. Sensemaking is used as a frame of reference for understanding accidents; it is used in relation to critical situations or complex operations in more general terms; it is described by some as a process creating situational awareness; and it is explained by others mainly in terms of how it relates to resilience. Sensemaking creates the context for being resilient; at the same time, sources of resilience help to make sense of the situation. Discrepancies must be supported by design, i.e., having redundant systems that can reveal discrepancies, and by training to ensure a questioning attitude. However, there is a lack of literature regarding sensemaking in safety-critical situations or in relation to resilience that also addresses aspects of training and system design. Sensemaking is crucial as the degree of digitalization, automation, and autonomy is increasing. Automation is based on codifying and handling past experiences, when the unexpected happens or the situation becomes more complex than automation can handle, then human intervention is needed. The human must make sense of a complex situation having been "out-of-the-loop" and try to recover the situation in order to achieve a safe state (i.e., being resilient). Thus, sensemaking and resilience are key issues during design and training (demanding high performance user design enabling understanding by a glance and recoverability/improvisation).

Based on the current literature review and other activities in the SMACS project, we mainly base our further work on sensemaking on the definition of Ref. [17]. Thus, we view sensemaking as a process that is prompted by violated expectations, that involves both attending to and bracketing cues in the environment with the aim to create intersubjective meaning through cycles of interpretation and action, enacting a more ordered environment from which further cues can be drawn. The pragmatic approach is to use sensemaking as a dynamic, iterative process of observing, orienting, and acting in a social setting, thereby creating a shared understanding. Sensemaking in critical situations is both retrospective and prospective, supporting how to build and adopt resilience through future actions.

Further work in the project will focus on how to improve the design of interfaces between humans and automation as well as training to facilitate sensemaking and resilience. Through this work, we aim to contribute to improve the ability to handle safety-critical situations in demanding maritime operations.

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