Safety performance monitoring of autonomous marine systems

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Abstract

The marine environment is vast, harsh, and challenging. Unanticipated faults and events might lead to loss of vessels, transported goods, collected scientific data, and business reputation. Hence, systems have to be in place that monitor the safety performance of operation and indicate if it drifts into an intolerable safety level. This article proposes a process for developing safety indicators for the operation of autonomous marine systems (AMS). The condition of safety barriers and resilience engineering form the basis for the development of safety indicators, synthesizing and further adjusting the dual assurance and the resilience based early warning indicator (REWI) approaches. The article locates the process for developing safety indicators in the system life cycle emphasizing a timely implementation of the safety indicators. The resulting safety indicators reflect safety in AMS operation and can assist in planning of operations, in daily operational decision-making, and identification of improvements. Operation of an autonomous underwater vehicle (AUV) exemplifies the process for developing safety indicators and their implementation. The case study shows that the proposed process leads to a comprehensive set of safety indicators. It is expected that application of the resulting safety indicators consequently will contribute to safer operation of current and future AMS.

Keywords: Safety indicators; autonomous marine systems; dual assurance; resilience

1 Introduction

Marine systems are becoming more automated and autonomous, with increasing technological complexity. In the future, autonomous marine systems (AMS), such as unmanned surface vessels, autonomous underwater vehicles (AUV), and other types of underwater robots will lead to improved maritime transportation, research of the oceans and arctic regions, military operations, and inspection and mainte-

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nance of subsea hydrocarbon production facilities [16, 31-33, 52, 53, 59]. This development is accelerated by the pressure to reduce costs, risks, and a demand for achieving more environmental friendly and sustainable operation.

Autonomy is a system's ability to make decisions, in order to fulfill a task, without the need for assistance of an operator or external agent during task performance [55]. An AMS is therefore not necessarily unmanned. The level of autonomy describes the degree and extent of decision-making, problem solving and strategy implementation of the system, when faced with uncertainty or unanticipated events [23]. Scales, e.g., from 1-10, for the level of autonomy range from manual control to full autonomy, of which the latter means no possibility for intervention from the operator. Levels in between include, for example, decision making by humans and implementation by the system, so called batch processing; shared plan generation and execution of tasks, where the operators still have full decision authority, so called shared control; and plan generation and execution by the system, where the operators only intervene if necessary, so called supervisory control [12]. Vagia et al. [55] give a comprehensive overview of different scales for levels of autonomy proposed in the literature. Not every AMS has the same level of autonomy in every subsystem or for each capability. For example, Insaurralde and Lane [23] differentiate between different problem-solving capabilities and the context for which the AUV is considered. Current AMS are not fully autonomous as they are supervised, with different ways of intervention from the operators, or they are remotely operated [38].

AMS can be operated with few or no human operators on board, which may decrease the risk of operation in relation to crew injuries and fatalities. Remote supervision and control, however, create risk in relation to other marine stakeholders, material assets, and the environment. During critical situations, which the AMS may not be capable of handling, operators have to take control and identify the right course of action, to avoid a potential incident. This requires high situation awareness of the operators and adequate input from support systems to handle such situations [3, 38]. Additional challenges are created by human interaction with the system during design, maintenance, or definition of overall mission goals [18]. The influence of the organization operating AMS is not negligible and has to be considered sufficiently during development and use.

Few publications cover risk in relation to AMS. Most of them focus on AUV, e.g., risk management [5, 50, 54], risk assessments [6-8, 13, 14], incident investigation [30, 47], or the influence of the human operators [17, 49]. Unmanned and autonomous ships are briefly analyzed [37, 38, 43, 44]. Huang et al. [21] propose a generic framework for deriving contextual performance metrics for unmanned systems, but do not cover safety, explicitly. In general, risk assessments and hazard identification should be reviewed, regularly [24]. Currently, review and subsequent updating, however, may be carried out after several years in operation. Changes in environmental, technical and organizational conditions may occur in shorter intervals than the reviews [27]. Hence, there is a need for indicators to measure safety performance and methods for analysis and monitoring of risk and safety during operation of AMS.

The objective of this article is to propose a structured process for developing safety indicators for AMS to be used for monitoring the operational safety performance of AMS. The methodological approach in the article is based on safety indicator development processes from high-risk industries, which are adjusted to the context of AMS. The feasibility and usefulness of the process is demonstrated for an AUV. The proposed safety indicators are evaluated for applicability in operational decision-making and safety monitoring. The process for developing safety indicators in this article addresses a company and system level, which means that an industrial or global industry scale are outside the scope, although some indicators might be also applicable on such a high level.

The next Section discusses the concepts of risk and safety indicators and methods for their development. This is followed by the description of a synthesized process for developing safety indicators based on the reviewed methods. Section 4 exemplifies the proposed process for developing safety indicators and presents safety indicators for an AUV. The last Section discusses and concludes the presented work.

2 Safety indicators

High-risk industries use risk and safety indicators to monitor the status of major hazards at an industrial level, e.g. [56], at a company level, e.g. [41], or at a single plant or unit of operation, e.g. [15, 46, 68]. Risk and safety indicators are specific for a certain organizational level. Indicators aiming at an industrial level might not be applicable to only one company or one specific plant.

Different definitions of risk and safety indicators are in use. Although used similarly and sometimes synonymously, risk and safety indicators are not the same. Risk indicators are derived from a risk based approach [64], e.g. [60, 61]. A risk indicator is the operational measurable variable related to a risk-influencing factor (RIF) in a risk model [64]. This article focuses on safety indicators. Safety is a condition where the remaining risk is accepted as sufficiently low [39], and safety indicators measure to which extent safety is present. Safety indicators include event indicators, barrier indicators, activity indicators, and programmatic indicators [68]. Øien [61] defines an indicator generally as "a measurable or operational variable that can be used to describe the condition of a broader phenomenon or aspect of reality". Here, the condition of a broader phenomenon is the level of safety in operation. Hence, a safety indicator is a measurable or an operational variable that can be used to describe the level of safety of operation. Swuste et al. [48] present and discuss other definitions in use in the scientific community and in different industries.

Two main types of safety indicators exist; occupational safety indicators and process safety indicators. Past accidents show that occupational safety indicators only cannot be used to monitor changes in process risk [15, 19, 27, 65], such as the Macondo Blowout in 2010 [10]. In this article, occupational safety indicators are excluded from further consideration, since few or no personnel will be on board the AMS during operation in the future.

Many safety indicator approaches distinguish between leading and lagging indicators. Hopkins [19] discusses the meaning and usefulness of this distinction. Essentially, a leading indicator indicates if the safety level of an organization is changing. However, actions can still be taken to avoid an accident [11, 26]. Lagging indicators include events that are considered an accident or incident. Leading and lagging indicators can be ambiguous terms [11, 19]. Hence, in this article, the terms "early warning" and "outcome" indicators are used in the context of AMS safety indicators, instead of leading and lagging indicators, in attempt to reduce any confusion. Early warning indicators provide information on an unsatisfactory performance of a safety barrier, related to preventing a potential incident [62]. Safety barriers can be physical or engineered systems, as well as human actions, which are guided by procedures or organizational initiatives. These shall prevent, control or mitigate harm from hazards [39]. An outcome indicator is an indicator related to the manifestation of undesired events. These reflect actual operational safety performance [22].

Different safety indicators consider different periods of change, since some changes occur slower than others [27]. Hence, efforts are made to capture fast changing safety factors, to include them in real-time safety monitoring, e.g., by Knegtering and Pasman [27], or Vinnem et al. [57].

To select an appropriate, complementary and manageable set of safety indicators, the proposed safety indicators have to be evaluated against a set of required characteristics [20, 22, 25, 26, 60, 65, 66]. Table 1 summarizes the characteristics from [22, 25, 26, 60], which are found particularly relevant for AMS. These will be used throughout this article.

Table 1 Selected safety indicator evaluation criteria, based on [22, 25, 26, 60].

	Safety indicator evaluation criteria
1	Relationship between safety indicator and safety is evident and understood
2	The safety indicator is observable and sufficiently measurable
3	Data is already collected or can be collected
4	Measurements are repeatable and verifiable
5	The safety indicator is robust against manipulation

2.1 Safety indicator development methods

Delatour et al. [9] and Øien [68] review and discuss methods for safety performance indicator development. Leveson [28] sets requirements for a good leading indicator development process. In short, it should be complete, consistent, effective, traceable, minimal, continually improving, and unbiased.

Two indicator development methods are found most suitable for further development and adjustment to the context of AMS; the dual assurance method [20], and the resilience based early warning indicators (REWI) method [66]. The dual assurance method provides an overview of the performance of important safety barriers. Especially, technical safety barriers, such as, sensor systems and collision avoidance systems, are relevant for AMS, since they give relevant input to the control system of the AMS and its operators. Furthermore, the method is a practical approach for safety indicators and widely accepted and used in the process industry [36]. However, other industries, which require a high level of confidence in their systems operating correctly and safely, can apply the approach [20]. Other approaches, such as API RP 754 [1], OECD Guidance No. 19 [34] and OGP Report No. 456 [35], are similar to the dual assurance method. However, they focus specifically on the release of hazardous materials, which is a more specific application area of less relevance for AMS.

In AMS operation, the operators have to be aware of the situation and be able to make the right decisions in those cases, where the AMS reaches its operational limits [38]. Many AMS today are still in development, unique or built in small numbers. Therefore, limited operational experience exists with AMSs making it important to monitor the supporting organization to ensure appropriate operation. REWI focuses on organizational performance to handle accidents, incidents and unexpected events. It aims at management decisions, appropriate communication within an organization and risk management, which is highly relevant for AMS. According to Øien and Paltrinieri [67], the dual assurance and the REWI methods provide effective and complementary means for developing safety indicators.

2.1.1 The dual assurance method

The UK health and safety executive (HSE) [20] developed the dual assurance approach together with the chemical and major hazard processing industry. The method assists in establishing key performance indicators for major hazards and process safety. The dual assurance method employs leading and lagging indicators and compares the lagging indicators to the leading indicators to reveal if the measured safety performance reflects the actual safety performance [20]; i.e., dual assurance. Safety indicators originate from the risk control systems (RCS) [20]. Reason's [40] layers of defense form the basis of the method. Organizational accidents arise due to inadequacies in the RCS, which promote active failures, leading to accidents. The RCS should be part of a safety management system, which focuses on a specific risk or activity [20]. Examples are sensors and alarms, the permit to work system, inspection and maintenance.

The dual assurance method is to some extent generic, even though it is developed for a chemical process plant. Hence, methodological adaptations to AMS are necessary, such as:

- The steps of the dual assurance development process have to be rearranged in order to fit it to the AMS' lifecycle.
- The term safety barrier, more commonly used in the marine industry, replaces RCS of the dual assurance method.
- The dual assurance method does not include consideration in terms of sampling intervals of the safety indicators, but these need to be defined for prudent use of indicators.

2.1.2 The resilience based early warning approach to development of indicators

The REWI method [66] was developed to prevent major accidents and to improve organizational safety and performance. The method is an extension of the leading indicators of the organizational health method, proposed by the US electric power research institute [63]. Resilience thinking forms the basis for the REWI method. Woods [58] describes resilience as the ability to recognize and adapt to unexpected changes in operation, in order to handle such changes. Therefore, a resilient organization is one that monitors its ability to foresee, recognize, and handle unexpected changes, and adjusts if these competences are not satisfying a certain level [42].

REWI [66] applies contributing success factors (CSF), derived from the attributes of resilience (risk awareness, response capacity, support), to develop the safety indicators. The CSF are risk understanding, anticipation, attention, response, robustness, resourcefulness/ rapidity, decision support and redundancy [51]. General issues defined by Øien et al. [43] describe considerations and practices, which apply to most high-risk industries and are necessary to achieve the CSF for a resilient organization. For these general issues, REWI proposes a set of measurable safety indicators, but leaves room for adding or adapting general issues and safety indicators to suit the organization and operation.

The REWI method aims at determining the organizational capabilities to handle unexpected and undesired situations, which might result in an accident. These are important aspects for the operation of AMS. Operators have to be prepared to make the right decisions and actions in case of failing systems. Especially, the CSF attention, response, resourcefulness/ rapidity and decision support are key factors in operation of AMS. Most of the general issues suggested in REWI are relevant for operation of AMS. Depending on its operating organization and its practices, other general issues and associated indicators may be necessary to identify.

By synthesizing the dual assurance and the REWI approaches, synergy effects are expected compared to applying the development processes individually. The expected benefits are reduced use of resources and time for identification of indicators, and a more adequate and comprehensive set of safety indicators. The resilience indicator process focuses on the CSF that are not covered sufficiently by the safety indicators related to safety barriers (dual assurance).

3 A process for developing safety indicators for autonomous marine systems

Figure 1 presents an overview of the proposed process for developing safety indicators, with five main steps and several sub steps. Detailed descriptions of each step follow in the next sub Sections.

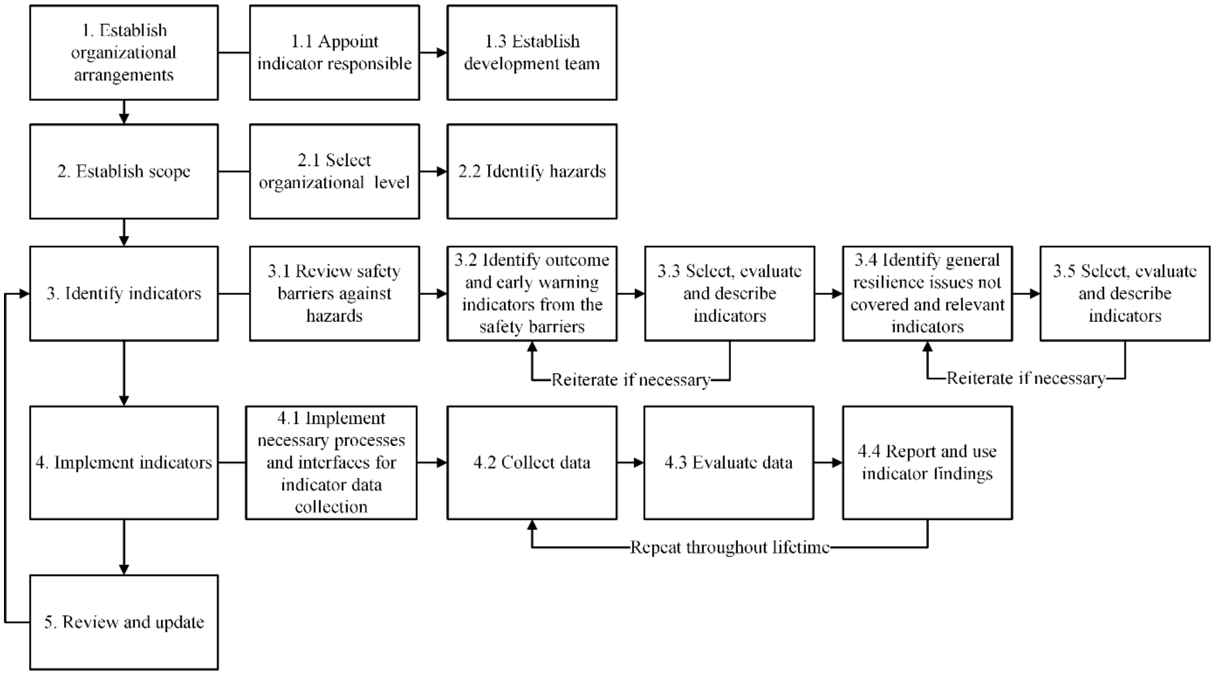

Figure 1 Steps in the synthesized process for developing safety indicators for AMS, based on [20, 66]

Figure 2 shows how the process for developing safety indicators relates to the life cycle phases of AMS, adapted from Blanchard [4]. The Figure includes the development, operational, and improvement processes that are undertaken during the major life cycle phases, the phases of the process for developing safety indicators and the feedback and input from the different phases and activities (dashed lines). The life cycle of AMS is divided into six phases, characterized by an initial top down approach starting at the system level in the conceptual design phase. Through the preliminary design and development phase, the focus gradually narrows down to the component and detailed design level, initiating a bottom up approach ending with system integration, testing and verification, before and during the commissioning of the AMS. The combined top-down and bottom-up approaches constitute the Vee model [4]. For efficient development and implementation, the process for developing safety indicators should start during the conceptual AMS design and progress as the system evolves and reaches its operational phase.

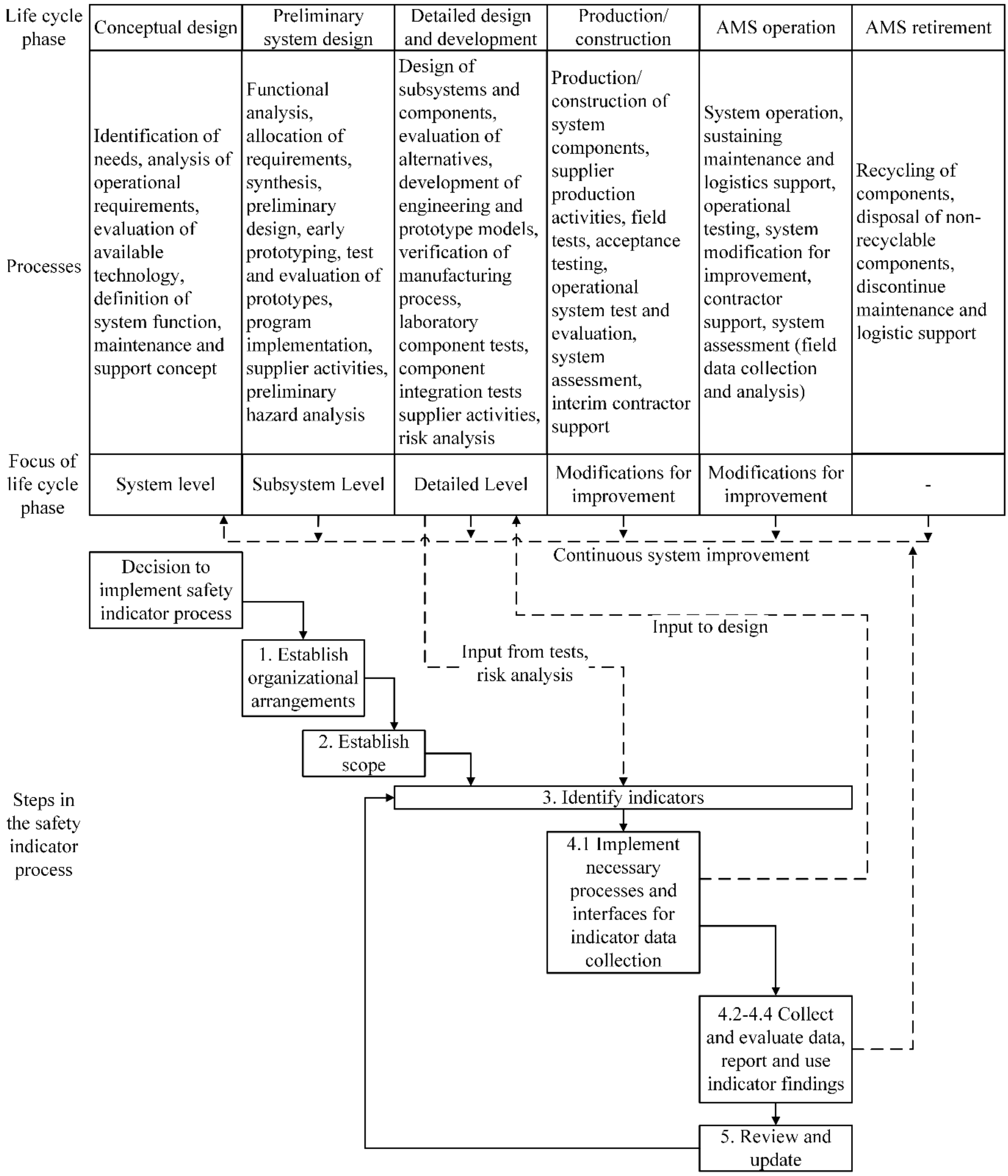

Figure 2 The process for developing safety indicators in relation to the system life cycle of an AMS (system lifecycle adapted from Blanchard [4], figure 1.12). Solid lines represent the sequential order of steps. Dashed lines represent feedback and feedforward of information and initiation of reiterations.

3.1 Establish organizational arrangements

A successful safety indicator system requires the commitment and trust of the management, in order to get required resources and support for development and use of the indicator system. The decision to implement a process for developing safety indicators for an AMS should be made during the conceptual design phase. Organizational arrangements are established during the preliminary design phase. A responsible for the indicator system should be appointed with support from management. He or she is responsible for organizing indicator development workshops, documentation of the safety indicators, indicator evaluation and presentation of indicator monitoring reports. The indicator system responsible appoints and commits the development team [66]. A development team should consist of four to eight people, including personnel who work in maintenance, operation, safety, and management. It might be beneficial to involve control and autonomy experts. Additionally, a secretary and a facilitator or mediator, to guide the indicator development workshops, are recommended. In the first indicator development workshop, the development team has to be introduced to safety indicators in general, common terminology, and the system itself [66]. Indicator development during the system design process has to utilize operational experience from operators with other similar existing systems, as well as qualified information and knowledge from the operators' point of view.

3.2 Establish scope

The second step is to establish the scope of the safety indicator system. This should occur during the preliminary design phase of the AMS and be finished with the beginning of detailed design and development, in order to ensure that meaningful safety indicators are identified and that the necessary interfaces for data collection are implemented timely in the system. The scope includes a description of the AMS, the organizational level the indicators aim at, major hazards, associated safety barriers, and their safe operational limits. In the context of AMS, the focus of the indicator system could be on one vessel, a fleet of vessels, the control center, or the company. For AMS, the major hazards are loss of AMS, or collision of AMS with other vessels or structures. The documentation of the scope should contain scenario descriptions and identification of underlying causes [20]. Available data should be used to define the hazards and underlying causes, and relevant safety barriers against these hazards.

3.3 Identify indicators

During the detailed design phase of the AMS, safety indicators should be identified. During the life of the AMS, this step is reiterated, in order to improve the safety monitoring process. New indicators may have to be identified and existing indicators may not be relevant any more or they may have to be adapted to changes in system operation.

The development team identifies three different types of safety indicators in two distinct phases: (i) outcome and (ii) early warning indicators related to safety barriers; and (iii) resilience indicators. Firstly, the indicators based on the safety barriers are established (type i and ii). A review of hazards and planned or implemented safety barriers identifies the most relevant safety barriers. It is not practical to develop safety indicators for all safety barriers. For this purpose, information is obtained from the detailed design phase activities and risk analysis. During risk analysis in the detailed design phase, the need for safety barriers are identified and evaluated, before the required safety barriers are designed in detail. The detailed design documentation of the safety barriers gives input to the process for developing safety indicators. Tests of components and component integration also give input to indicator development by highlighting areas that need special attention in relation to risk.

For each relevant safety barrier, the desired safety goal is described, which summarizes its expected performance and achievements. Outcome indicators reflect a failure of the desired safety outcome, e.g., an accident, near miss, incident. A description of critical elements of the safety barrier gives input to the development of early warning indicators. Early warning indicators reflect the performance of critical elements of the safety barrier, e.g., the performance of associated subsystems. For each relevant safety barrier, at least one outcome and one early warning indicator are required. All proposed indicators should be evaluated against the criteria in Table 1. If none of the proposed indicators fulfills the criteria, the development team has to reiterate steps 3.2 and 3.3 in Figure 1.

In the second phase of the indicator identification step, resilience indicators (type iii) that complement the early warning indicators related to safety barriers are identified. The resilience indicators are also early warning indicators, but are not related to safety barriers. Hence, they are called resilience indicators in the following. Each of the already identified early warning indicators related to safety barriers (type ii) is associated with one CSF and a corresponding general issue (cf. Section 2). For AUV, the CSF and general issues are adapted from REWI [66]. These are the following: Risk understanding – information about quality of barrier support functions, risk understanding – information about quality of barriers, anticipation – risk/ hazard identification, attention – changes, response – flexibility of organizational structure, robustness – communication between actors, resourcefulness/ rapidity – adequate ICT systems, decisions support – adequate ICT decision support systems, redundancy – redundancy in information processing. In order to represent the planning process of an AUV mission, a new general issue, called mission/ operation characteristics, is added to the CSF anticipation.

The development team assesses suitable indicators for the general issues. Each general issue should be covered by at least one early warning indicator, which means that those general issues not covered by the early warning indicators from phase one should be covered by resilience indicators in phase two. Evaluation of all resilience indicators against the criteria in Table 1 is necessary in order to ensure a usable set of indicators. If not enough resilience indicators satisfy the criteria, the steps 3.4 and 3.5 in Figure 1 must be reiterated, in order to achieve a comprehensive set of safety early warning indicators.

Each safety indicator has to be thoroughly described. The description should include several aspects: the desired (qualitative) safety goal, critical elements associated with the indicators, data requirements, data sources, sampling intervals, indicator thresholds, safety improvement measures if critical thresholds are reached, and relevant references. Before data and information for the indicators can be collected, necessary interfaces, procedures and processes have to be defined and implemented. This influences the detailed design phase (Figure 2), because it is necessary to ensure that these interfaces are designed appropriately.

One important aspect of using safety indicators is the sampling interval [27]. Three sampling categories should be considered: short-term, mid-term and long term. Collection of data for short-term indicators occurs at least once per day, but could also be every second or minute. Sampling of data for mid-term indicators occurs at least once a week, but not more often than once per day. Long-term indicators are monitored at least once a month (30 days), but not more often than once a week. Any early warning indicators collected less than once a month might be dismissed from further inclusion in the safety indicator system [66].

Determining the indicator thresholds is another challenge. Hassan and Khan [15], for example, use four classes of risk, which are associated with an index range: Extreme, high, medium, and low. For safety indicators, critical, low, medium, and high, are proposed as classes or thresholds. "Critical", for example, means that the safety threshold is very close to being violated, whereas "high" means that the safety performance is good. Another example for deriving threshold values is given by Saqib and Siddiqi [45], using percentiles of defined requirements. For each safety indicator, such thresholds should be defined individually. Table 2 presents threshold examples for outcome, early warning, and resilience indicators.

Table 2 Examples of safety indicator thresholds, based on [15] and [45]

		Safety threshold (exemplary)	
Safety rank	**Safety class**	**Early warning indicator or resilience indicator [%]**	**Outcome indicator [# of occurrences in a period]**
1	Critical	0 – 75	5
2	Low	> 75 – 85	3
3	Medium	> 85 – 95	1
4	High	> 95	0

3.4 Implement indicators

The implementation of the indicator system has to be prepared in the detailed design phase, in order to provide the right interfaces for collection of data and measurement of the indicators. If the implementation is started too late in the detailed design phase, design reviews might be necessary during construction and commissioning, which may delay the completion of the AMS. Information that is already collected should be used, if possible. Ideally, automated systems should be in place to collect data for short-term safety indicators and evaluate them. Otherwise the indicators may be too resource intensive to be used efficiently and distract the operators and indicator system responsible from their actual tasks.

During AMS operation, the safety indicator system is used and reviewed regularly. Data has to be collected and evaluated on a regular basis. Analysis of the absolute indicator values reflects the safety level during a specific period. Indicators that are measured in a low or critical safety class trigger the defined safety improvement measures with respect to upper and lower thresholds. These safety improvement measures are dependent on the type of safety indicator, but will lead to input for system improvement.

Trend analysis might add additional information to the monitoring of safety [29]. Especially for indicators, which cannot be measured often, trends might indicate a degradation of the system before thresholds are exceeded. Some outcome indicators represent undesired incidents and do not occur often. Hence, capturing and analyzing data may prove to be difficult. A comparison of outcome and early warning indicators' development gives information on how well the early warning indicators reflect actual safety performance. If their developments differ too much from each other, a review of the set of indicators is necessary.

Øien et al. [66] propose quarterly reporting to follow up on the safety indicators. This is the task of the indicator system responsible. He or she should also present the results to management and initiate discussion of necessary safety improvement measures to be taken in order to improve the safety level. This discussion should involve relevant personnel, e.g., managers, operators, technicians, or engineers. Cause analysis of undesired outcomes can give input to finding more suitable safety indicators [62].

3.5 Review and update

The last step of the process for developing safety indicators is to review the indicators and their implementation regularly during the AMS operation phase. This ensures that the indicators reflect operation and overreliance effects are counteracted [66]. This also requires a review of hazards and operational conditions, i.e., have modifications been undertaken, or new hazards been identified. Input from field tests, the operators and operational data give insights into safety relevant issues that need to be monitored. A workshop approach, as used in the development phase, might add value to the review. Especially, feedback from those gathering data and monitoring the indicators might lead to an improved safety indicator system. Thresholds can be adapted and refined with the operational experience collected. New indicators can be identified and implemented, in order to improve the safety monitoring of the AMS. Discarding and replacement of inadequate and inefficient indicators is one of the tasks. The documentation of the indicator system should reflect how and why changes have been executed. This knowledge is valuable for future indicator systems and enable the organization to build better safety indicator systems for AMS.

4 Exemplification of the process for developing safety indicators

This Section exemplifies the use of the presented process for developing safety indicators based on operation of an AUV, i.e., the REMUS 100, which is discussed, e.g., in [14, 47, 50]. NTNU operates one REMUS 100 through the AUR Lab [2]. AUVs are used, for example, in mine counter operations, seafloor mapping, medium- and large-scale surveys of seawater properties, and inspection of subsea installations [59]. AUVs are cigar-shaped and follow a pre-programmed mission path. The operators supervise the AUV onshore or onboard a ship or a working vessel. The AUV should detect unexpected or undesired events, abort the mission and return to a meeting point. However, operators might also have to abort the mission, due to deteriorating performance or deteriorating (environmental) conditions. In this case, the operators detect problems and react appropriately. Furthermore, if a mission is finished or aborted, automatically or manually, operators have to be prepared to retrieve the AUV at a meeting point.

Operators carry out maintenance, mission preparation and planning, the missions itself and post mission tasks. Operation here refers to six different phases: mission planning and preparation, deployment, mission execution, retrieval and post mission tasks, inspection and maintenance, and data and mission analysis. Loss of an AUV may occur during deployment, mission execution or retrieval. All phases of an operation are relevant to consider with respect to development of indicators. Currently, measurement and trending of some indicators may have to take place after a mission, since not all data is submitted from the AUV to the operators during a mission.

The application of the process for developing safety indicators is covered only superficially with respect to the organizational arrangements, updating, and review. The focus of this example is on identification of indicators and considerations for implementation.

4.1 Organizational arrangements and scope

The safety indicator system aims at reflecting the safety level of operation of a REMUS 100 AUV. It focuses on the operators and their ability to handle unexpected situations and the recovery of the AUV. Loss of the AUV is the main hazard. Causes for loss can be faults of internal (electronic) components, intrusion of water in the AUV, and wrong planning [47, 50]. Immediate causes for internal faults, can be found in setup errors, faulty components, unforeseen interactions and software faults [54]. Causes for water intrusion might be damages due to improper handling, collision, maintenance or through improper sealing of the propulsion system [47, 50]. Causes for insufficient planning are typically erroneous estimation of environmental factors, erroneous implementation of parameters and waypoints, and insufficient solving of existing faults [30, 47, 50, 54].

Table 3 gives an overview of hazards for AUV operation and associated safety barriers, adapted from [20]. The Table summarizes the safety barriers in the left column and associated hazards and basic causes in the right columns. Inspection and maintenance refer to the detection and subsequent repair of damages and degradations of the AUV. Procedures refer to the instructions given to the operators, to ensure appropriate maintenance and inspection, correct planning, correct set up of the AUV, and solving of existing faults of the AUV. Instrumentation and alarms refer to self-tests and sensors that detect if the AUV is working as supposed and indicate this to the operator. Communication includes the exchange of safety critical information between the AUV and operators, and among operators. Emergency arrangements refer to those actions that have to be taken after a self-test has detected a critical fault and the retrieval of the AUV after a mission.

Table 3 Hazards and safety barriers for AUV operations, adapted from [20] and based on [30, 47, 50, 54]

Safety barriers	**Causes for loss of AUV**		
	Water intrusion	**Insufficient planning**	**Internal faults**
1. Inspection and maintenance	x		x
2. Procedures for:			
Mission preparation	x	x	
Operation of the AUV			x
3. Instrumentation and alarms	x	x	x
4. Communication:			
Between AUV and operators			x
Between operators	x	x	
5. Emergency arrangements	x	x	x

4.2 Identify indicators

The safety barrier instrumentation and alarms exemplify the further steps of the process for developing safety indicators related to safety barriers. The AUV is equipped to detect leaks, ground faults, temperatures and pressures out of operational limits. Ideally, sensors detect faults and trigger alarms that indicate these faults through the monitoring interface to the operator; however, false alarms may occur. Based on Table 3 and the above description, two outcome indicators can be identified: *Number of times water detection sensors inside the AUV do not detect water intrusion* and *number of times safety critical faults do not lead AUV to abort mission*. One critical element of the safety barrier instrumentation and alarms is that the AUV's sensors detect its current state correctly and sufficiently. A second critical element is that alarms are activated in a timely manner and that they raise sufficient awareness of the operator. *Percentage of faults related to critical subsystems detected by self-tests*, and *percentage of time critical sensors work without fault,* are therefore two possible early warning indicators. Table 4 evaluates the four proposed safety indicators, for the safety barrier instrumentation and alarms, against the requirements set in Table 1.

The evaluation in Table 4 shows that a suitable outcome indicator is *number of times water detection sensors inside the AUV do not detect water intrusion.* Sensors in the lower half of the AUV should detect water intrusion, leading to an immediate mission abort when they detect water. If these should not work, the operators would detect water intrusion after the mission during cleaning and inspection of the AUV. A suitable early warning indicator is the *percentage of time critical sensors work without fault*. Examples of critical sensors are leak detection and grounding error detection.

Table 4 Evaluation of proposed safety indicators for the safety barrier instrumentation and alarms

Safety indicator evaluation criterion	**Safety indicators**			
	Number of times safety critical faults do not lead AUV to abort mission	**Number of times water detection sensors inside the AUV do not detect water intrusion**	**Percentage of faults related to critical subsystems detected by self-tests**	**Percentage of time critical sensors work without fault**
1	YES, if the AUV is not aborting automatically, it will be difficult for the operator to identify the situation as critical.	YES, if a water ingress in the AUV body is not detected, the AUV is highly endangered.	YES, faults in critical subsystems that are detected are known and can be catered for.	YES, a high availability of sensor systems gives confidence that abnormal situations will be detected.
2	NO, difficult to measure. A proper definition of safety critical alarm is necessary.	YES, if the AUV is retrieved and maintained, the water intrusion will be found. This is a rare event.	NO, not all critical faults might be detected after a mission, without the self-test.	YES, faults of sensors are readily recorded and can be observed.
3	Data can be extracted from fault and mission logs.	Data can be extracted from fault, mission and maintenance logs.	Data can be extracted from fault, mission and maintenance logs.	Data can be extracted from fault and mission logs.
4	PARTLY, data might be subject to interpretation and hence different values may be produced.	PARTLY, mission and maintenance documentation provides unambiguous data.	PARTLY, measurements are subject to evaluation and interpretation of data.	YES.
5	NO, due to the manual evaluation and assessment of faults, the indicator might be subject to different interpretations and manipulation.	PARTLY, if the maintenance logs are not kept properly, the indicator might be manipulated.	NO, might be subject to manipulation, due to detectability of the faults.	YES, data is recorded automatically.
	NOT SELECTED, difficult to implement and measure.	SELECTED, the indicator is specific enough to reflect safety of operation.	NOT SELECTED, measurement difficult and ambiguous.	SELECTED

Table 5 describes these two selected safety indicators in detail for use in the safety indicator system. The description contains the required elements stated in Section 3.3. The desired safety goal of the safety barriers describes their expected performance. In respect to the two selected safety indicators, critical sensors should operate during a mission and warn if an undesired event occurs. For both safety indicators, it is critical that the sensors are set up and calibrated to detect undesired events and that they react timely to an undesired event and trigger associated alarms. For the early warning indicator *percentage of time critical sensors work without fault*, it is important to define and select these critical sensors and associated fault messages in the fault logs. The *percentage of time critical sensors work without fault* can be sampled during a mission or after a mission. Since water intrusion is a rare event, *number of times water detection sensors inside the AUV do not detect water intrusion* can only be sampled monthly. If one of the safety indicators should be found in the critical or low safety class, the associated actions described in Table 5 should come into action. In the case of the two selected safety indicators, the causes for the faults should be identified and actions taken against reoccurrence. References for such an investigation might be found in the manuals of the AUV.

All safety barriers should have at least one outcome and one early warning indicator (cf. Section 3.3). Thus, Table 6 and Table 7 propose a set of outcome indicators and early warning indicators for all five types of safety barriers, respectively (cf. Table 3). O3 and EW3 are described in detail. The other identified safety indicators are not detailed here, due to space limits.

Table 5 Description of selected safety indicators for the safety barrier instrumentation and alarms

		O3: Number of times water detection sensors inside the AUV do not detect water intrusion	**EW 3: Percentage of time critical sensors work without fault**
Desired safety goal		If water should enter the sealed AUV body this has to be detected, mission aborted and a warning sent to the operators.	Sensors covering vital functions of the AUV should work continuously during a mission and detect relevant faults if they occur.
Critical elements		Sensors have to react to small amounts of water entering the body. Alarms have to be triggered immediately and a notification send to the operators.	Adequate thresholds for relevant sensors to trigger alarms. Adequate sensors for operating conditions.
Data requirements		-	Definition of critical sensors necessary and identification of associated faults recorded in the fault logs.
Data sources		Water intrusion has to be identified manually and compared with fault logs.	Fault logs and mission logs.
Sampling intervals		Monthly.	During or after mission.
Thresholds	Critical	2 and more are critical	≤97.5
	Low	1	>97.5 – 99.0
	Medium	-	>99.0 – 99.5
	High	0	≥99.5
Actions		Identify causes for water intrusion. Implement measures against reoccurrence. Send in AUV to supplier for repair.	Identify main contributors to the decreased performance. Identify causes and implement measures against reoccurrence.
References		Manuals for maintenance and inspection	Manuals for maintenance, inspection and operation
Associated resilience attribute, CSF and general issue		None – outcome indicator	Risk awareness – risk understanding – information about the quality of barriers

Table 6 Proposed outcome indicators for all identified safety barriers of AUV operation

	Outcome indicator	Safety barriers	Sampling interval
O1	Number of faults that can be traced back to erroneous or lacking maintenance	Inspection and maintenance	Monthly
O2	Number of incidents where necessary procedures were not available during a mission	Procedures	Monthly
O3	Number of times water detection sensors inside the AUV do not detect water intrusion	Instrumentation and alarms	Monthly
O4	Percentage of missions where connection between operators and AUV was lost unplanned for more than 30 minutes	Communication	Monthly
O5	Number of (temporary) losses of AUV	Emergency procedures	Monthly

Table 7 Proposed early warning indicators for all identified safety barriers of AUV operation

	Early warning indicator	Safety barriers	Resilience attribute – CSF – general issue	Sampling interval
EW1	Percentage of maintenance and inspections completed in specified periods	Inspection and maintenance	Risk awareness – risk understanding – information about quality of barrier support functions	Monthly
EW2	Percentage of procedures updated and revised in the designated periods	Procedures	Risk awareness – risk understanding – information about quality of barrier support functions	Monthly
EW3	Percentage of time, critical sensors work without fault	Instrumentation and alarms	Risk awareness – risk understanding – information about quality of barriers	During or after a mission
EW4	Percentage of anticipated status messages received from the AUV	Communication	Response capacity – robustness – communication between actors	During or after a mission
EW5	Percentage of successful recoveries of AUV within 15 minutes after end of mission or preliminary mission abort	Emergency procedures	Response capacity – response – flexibility of organizational structure	Monthly

The early warning indicators related to safety barriers cover the CSF: risk understanding, robustness and response. Table 8 proposes resilience indicators related to the remaining CSF: Anticipation, attention, resourcefulness/ rapidity, decision support and redundancy. Relevant general issues were selected, based on their suitability for AUV operation. The resilience indicators were developed and refined in order to reflect AUV operation for these general issues. The resilience indicators in Table 8 are motivated by [66], and focus on the adequacy of the ICT system and associated functions, but also organizational learning and awareness for the environment. Figure 3, adapted from [66], visualizes how the identified early warning indicators presented in Table 7 and the resilience indicators in Table 8 are linked to the CSFs and general issues.

Table 8 Proposed resilience indicators for AUV operation, motivated by [43].

	Resilience indicator	**Resilience attribute – CSF – general issue**	**Reasoning**	**Sampling frequency**
R1	Percentage of missions that have been discussed in terms of hazards and risks before mission start	Risk awareness – anticipation – risk/ hazard identification	Being aware of possible hazards and risks for a certain area prepares the operators to plan and prepare for the mission accordingly.	Monthly
R2	Number of contacts between AUV and seafloor per hour, during a mission	Risk awareness – anticipation – mission characteristics	Knowing the conditions and characteristics of the mission environment is important in order to set up the AUV correctly for a mission. If the AUV has frequent contact with the sea floor, it was not set up correctly for the topography of the sea floor. This indicates an insufficient planning process.	After a mission
R3	Percentage of missions where environmental conditions exceeded the allowable limits	Risk awareness – attention – changes (environmental)	Monitoring changes is an important task of the operators, especially in respect to sea state and weather.	Monthly
R4	Average time between status messages	Response capacity – resourcefulness/ rapidity – adequate ICT systems	Without adequate knowledge of occurrences, a timely response is not possible.	During or after a mission
R5	Percentage of missions where monitoring laptop was (partly) not available during a mission (e.g., due to low battery)	Support – decision support – adequate ICT decision support	A monitoring laptop displays all critical information about the AUV and allows for change and adaption of the mission plan.	Monthly
R6	Number of alternatively available communication channels between AUV and operators during a mission	Support – redundancy – redundancy in information processing	Without information from the AUV, the operators do not know about the state and intentions of the AUV. Especially during retrieval, where the position must be communicated.	During or after a mission

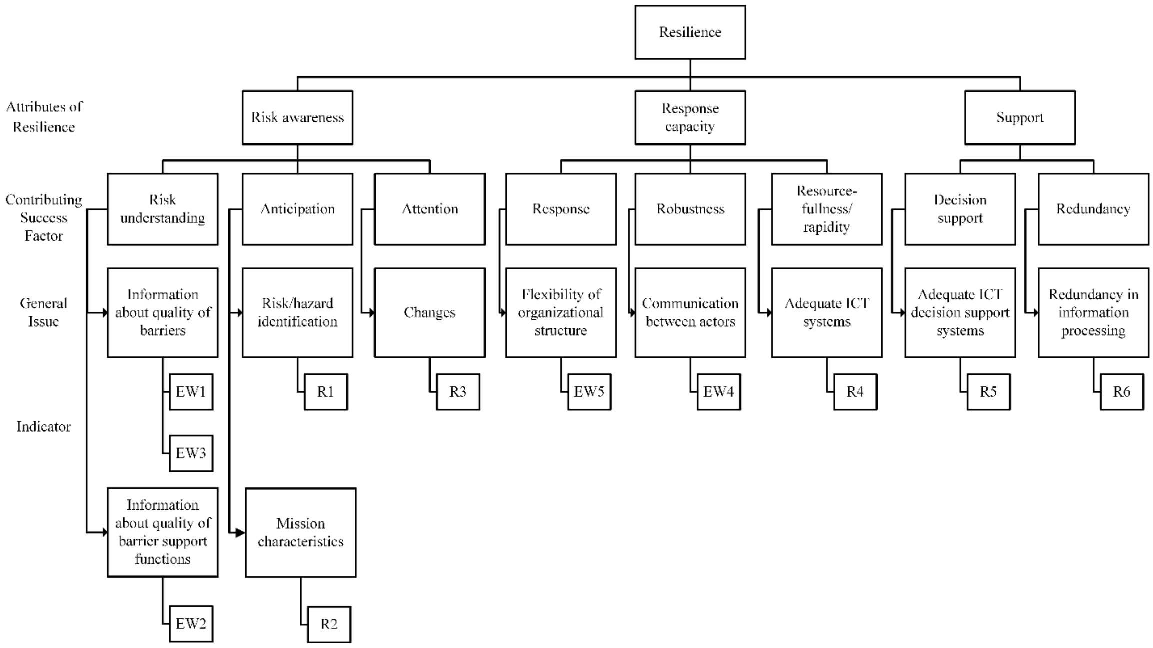

Figure 3 The proposed early warning indicators and resilience indicators related to the resilience attributes, the CSFs, and the general issues, adapted from [66].

4.3 Indicator implementation

Nine missions of the NTNU AUR Lab were analyzed for gathering input data for testing the indicators. The data were recorded in the electronic mission and fault logs, which are created by the AUV. The NTNU AUR Lab carried out these missions between 06. August and 19. November 2015. The analysis revealed which information is already recorded in the electronic mission or fault logs and which information might be recorded or extracted with some additional effort. Table 9 summarizes the data availability.

Several safety indicators can be captured automatically from the electronic mission and fault logs, e.g., O3, EW1, EW3, EW4, EW5, R2, R3 and R5. Algorithms for their automatic evaluation would reduce the manual work associated with the safety indicator system. Several of the proposed safety indicators need manual collection, e.g., from an AUV journal or a computerized maintenance management system, where operators record performed inspections/ maintenance (for EW1), incidents before or during operation (O1, R4), and changes in procedures (EW2). Other safety indicators can also benefit from such documentation, especially the outcome indicators. Procedures and programs for collection of data for the indicators still need to be implemented for several of the proposed safety indicators. Hence, not all safety indicators could be assessed for the NTNU AUR Lab missions.

Table 9 Data sources for the proposed safety indicators

	Data source			
Safety Indicators	**Already found in mission logs collected by the AUV**	**Already found in fault logs collected by the AUV**	**Data collection in the AUV's mission/ fault logs possible**	**Manual documentation/ collection necessary**
O1		Partly		Yes
O2				Yes
O3		Partly		Yes
O4			Partly	Yes
O5	Partly			Yes
EW1				Yes
EW2				Yes
EW3		Yes		
EW4	Partly		Yes	
EW5	Partly		Yes	
R1				Yes
R2		Yes		
R3				Yes
R4	Partly		Yes	
R5				Yes
R6	Partly	Partly	Yes	

Figure 4 presents the number of recorded faults per hour of operation for each of the missions. None of these faults is relevant for the sensor system. Most of the recorded faults correspond to warnings, e.g., problems in the compass bias table, or the "vehicle stuck on surface; attempting to drive it down". These fault messages are common warnings, and do not affect the mission execution, because the AUV is not endangered, c.f. [14]. Only mission number 6 had to be aborted, due to a failure in the thrusters. Causes and subsequent actions were not recorded, which means that causal analysis is not possible. Hence, the current documentation would need to be adapted to use the proposed indicators efficiently.

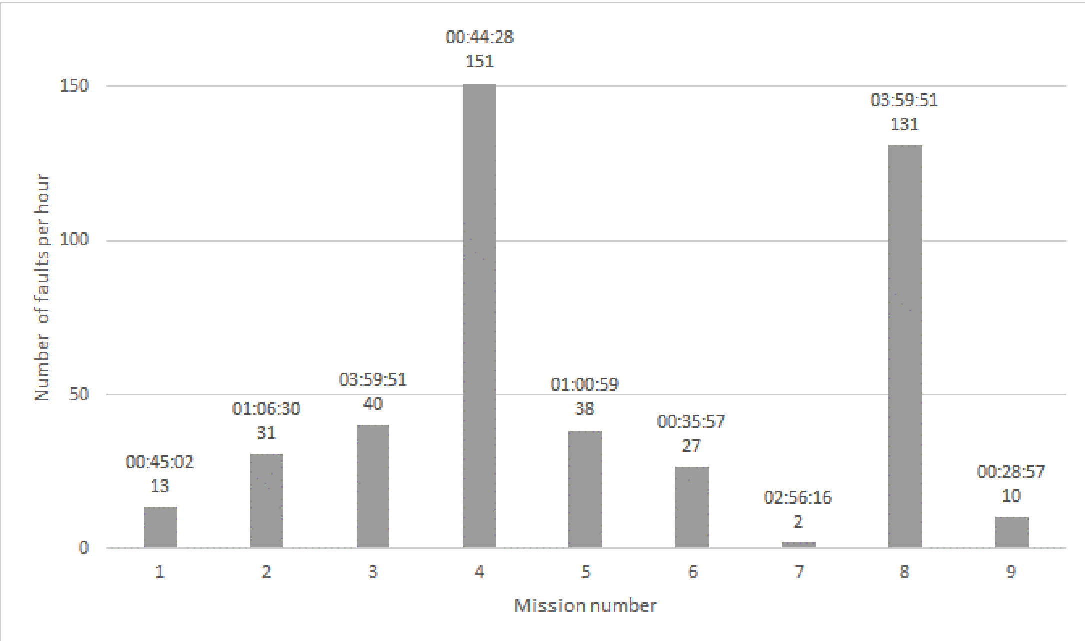

Figure 4 Number of faults per hour of operation recorded during nine missions of the REMUS 100 of the NTNU AUR Lab between 06. August 2015 and 19. November 2015. Total mission time is displayed above the number of faults.

The indicator system responsible should carry out evaluation of the safety indicators and prepare the reports and distribution of the results. If trends or safety indicator values show degradation of operation, safety improvement measures have to be taken to improve operation. Additionally, incidents and problems should be discussed with relevant stakeholders. For example, for the indicator R2, two relevant fault messages are recorded. These are "Vehicle at low altitude. Executing emergency climb", and "Vehicle stuck on bottom, attempting to float free". Several instances of these have been recorded in the missions 4, 5, and 8, shown as "contacts with seabed" in Figure 5. This shows that in three missions assessment of the environment might have been insufficient. Especially mission number 5 had a high rate of contacts between AUV and Seabed. For that mission, it should be analyzed why so many contacts occurred and how that could be prevented in the future in the planning process of a mission. EW 4 can be directly assessed from the fault logs. During the nine recorded missions, no critical sensors failed.

Hence, the safety indicator did not reveal any deficiencies. During the next review, this early warning indicator should be checked for relevance, since critical sensor faults seem not to occur often enough to indicate safe operation.

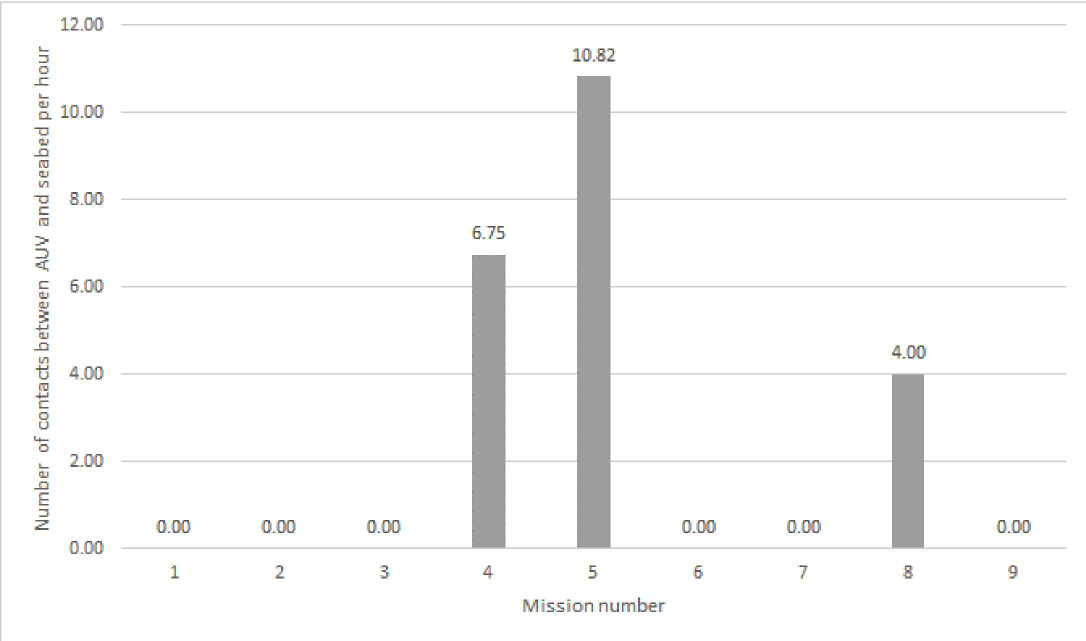

Figure 5 Number of contacts between AUV and seabed per hour of operation, recorded during nine missions of the REMUS 100 of the NTNU AUR Lab between 06. August 2015 and 19. November 2015.

5 Discussion and conclusion

The proposed process for developing safety indicators in this article is based on two methods from high-risk industries, which are synthesized and adjusted to the application area of AMS. Currently, no structured process for developing safety indicators for AMS exists or is in use. HSE and REWI processes are complementary [67], and the article shows how the two methods can be integrated, adapted to AMS, and applied jointly. The presented process for developing safety indicators focuses efforts, resources and attention to identify a sufficiently comprehensive, but still a manageable set of safety indicators. The dual assurance and REWI methods, if applied separately, would overlook important safety aspects [29, 65]. Thus, the proposed process for developing safety indicators finds a coherent set of safety indicators that covers the company, aiming for complete coverage of safety aspects.

This article locates the steps of the process for developing safety indicators in the system life cycle of an AMS. The process for developing safety indicators is most efficient if it is implemented during the design of the AMS, and then further refined based on operational experience. Necessary interfaces and systems for indicator collection can be developed in the detailed design phase, which may reduce implementation costs and benefit the overall system design. The case study shows that implementing the process for developing safety indicators during the operation phase of a system is challenging concerning collection of the safety indicators. Additional effort is necessary to create necessary interfaces, and implement procedures and processes for safety indicator development.

The development team could cooperate with the system safety analysts to establish a relationship between risk assessments and the safety indicators. This would in return overcome some deficiencies of the two methods, as mentioned by Øien [68], for example, the missing link to risk models. Comparison of outcome indicators and early warning indicators helps to evaluate and validate safety performance and to reveal deficiencies in the safety indicator system. If the performance of early warning and outcome indicators differs too much, the safety indicators have to be reviewed with respect to usefulness and efficiency. Generally, the safety indicator system should be reevaluated regularly, in order to improve the system.

In the example of an AUV, the process for developing safety indicators results in five outcome indicators and eleven early warning indicators. Twenty safety indicators is the suggested upper limit by Øien et al. [66] for the REWI method. Likely, there will be more than 20 safety indicators for more complex systems with the suggested process for developing safety indicators. However, if the safety indicators can be collected by a computer system, with little human labor required, more than 20 safety indicators should be manageable. Generally, the amount of safety indicators depends on the target organizational level and the organizational capabilities. The safety indicators in this article cover both direct safety functions, e.g., alarms, and broader aspects of safety functions, such as maintenance, which has an essential influence on safety, even though maintenance alone does not guarantee safe operation [56]. A relationship between safety and the safety indicators is inferred, but not demonstrated. It is assumed that the relationships between the safety indicators and safety in other industries are also valid for operation of AMS.

Regarding the safety indicator development example, some more limitations have to be mentioned. The system was chosen for its simplicity and accessibility as an AMS. The suggested process for developing safety indicators and management of safety indicators may be resource demanding for an organization operating one REMUS 100 AUV, only. Some of the identified safety indicators, however, apply to other AMS, as well. Some safety indicators are similar to the findings of Rødseth et al. [43, p. 30 ff.]. To investigate its capabilities in a broader sense, the proposed process for developing safety indicators should be applied to other AMS, such as autonomous or unmanned ships, or operation of multiple AMS. This can complement efforts, such as Rødseth et al.'s [43], in a structured manner.

Due to changes of season, sea state and weather, it may be difficult to collect some safety indicators regularly and unbiased. Examples are *percentage of missions that have been discussed in terms of hazards and risks before mission start*, *percentage of missions where environmental conditions exceeded* *the allowable limits, e.g., wave height, wind speed*, or *percentage of maintenance and inspections completed in specified periods*. These safety indicators are highly dependent on the amount of missions executed. For AMS, which are operated frequently, such concerns are less relevant.

Most of the proposed safety indicators can be collected from the fault logs, or captured if some more data is recorded automatically. Currently, manual evaluation and investigation is necessary for several safety indicators. This makes the implementation difficult and additional procedures and systems need to be put into operation for the collection of these safety indicators. This applies to, e.g., *number of faults that can be traced back to erroneous or lacking maintenance, percentage of missions that have been discussed in terms of hazards and risks before mission start*, or *number of alternatively available communication channels between AUV and operators during a mission*.

Some of the proposed safety indicators for AUV operation can be sampled in short-term intervals, e.g., *number of alternatively available communication channels between AUV and operators during a mission*, *number of contacts between AUV and seafloor per hour, during a mission,* or *percentage of anticipated status messages received from the AUV*. These safety indicators could be used during operation to assess how well the AMS performs in real-time with respect to safety. Further investigation is necessary to develop and implement a real-time or online safety monitoring systems for AMS. On the other hand, for some of the proposed safety indicators that are not updated often enough, e.g., *percentage of procedures updated and revised in the designated periods*, safety audits might be a more suitable tool. Further investigation is needed regarding the feasibility of both an online safety monitoring system and safety audits for AMS.

Acknowledgements

The authors wish to thank the anonymous reviewers for their valuable comments. The support by the NTNU AUR Lab, providing mission and fault data, is acknowledged. Thanks to Jeevith Hegde for useful comments on a draft version of this article. Comments from the participants of the doctoral degree course *System Safety Engineering and Management* on an early version of this article are appreciated.

This work was supported by the Research Council of Norway through the Centres of Excellence funding scheme, Project number 223254 – AMOS.

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