# Design Considerations for Auditory Alarms in the Process Industry: A Systematic Literature Review

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# Abstract

This study focuses on the research of design methodologies on the topic of auditory alarms in the context of the process industry. The overall goal of this research is to provide input for both process companies and auditory alarm designers for future development. Specifically, this study uses a systematic literature review on previous peer-reviewed papers on the design and characteristics of auditory alarms in the process industry. The background chapter will provide basic understanding of different factors to consider when designing auditory alarms.

Results identified in from the SLR are that there is little research done in this area. Eight papers was included, and these provided insight from on how the design methodology should be handled in accordance to industry standards, specified characteristics of auditory alarms and human factors considerations. By design, the standards have more of a focus on *what to do* rather than *how to do it,* where it can become a challenge for auditory alarm designers. The provided results from the systematic literature review and standards can be used as a simplified guidance on the design of auditory alarms intended for both the use in the process industry, but also for other control room applications.

Further research on this topic would be on the improvement effects of implementing new/redesigned auditory alarm systems, in relation to the standards set by the industry today. Further design and experimental testing of auditory alarms should be considered from human factors point of view, where both the standards and literature suggests this to be the most effective design for operators.

**Keywords**: Auditory Alarms, Process Industry, Control Room, Systematic Review

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I also want to thank Equinor for giving me access to information, and letting me participate in workshops for their auditory alarm realization project.

Finally, I am most of all indebted to my partner Frida for her support and encouragement over the course of this journey. A special thanks to my family for providing me support when it was needed during this long phase of studying. I am confident in saying that this would not have been possible without your support.

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# List of Abbreviations

| | |
|---|---|
| CCR | Central Control Room |
| CROPs | Control Room Operators |
| CROPs | Control Room Operators |
| EEMUA | Alarm systems: Guide to design, management and procurement |
| GEMS | Generic Error-Modelling System |
| IEC | International Electrotechnical Commission |
| IMO | International Maritime Organization |
| ISA | The International Society of Automation |
| OD | Norwegian Petroleum Directorate |
| PICOC | Population, Intervention, Comparison, Outcome, Context |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| PSA | Petroleum Safety Authority Norway |
| SAS | Safety Automation System |
| SLR | Systematic Literature Review |

# 1. Introduction

## *1.1 The problem/challenge*

Auditory warnings have an important role in attracting attention and conveying information in many work areas including hospitals, aircraft, automobiles and factories (Edworthy & Stanton, 1995). In the context of process industries there are a lot of factors that go into the consideration of their alarm system. The definition of the term *alarm* is often dependent on its purpose; Stanton (1994, p. 6) gives the following definition: “An unexpected change in system state, a means of signaling state changes, a means of attracting attention, a means of arousing the operator, and a change in the operator’s mental state”.

While the content of an alarm is presented visually, the “attention-getting” role of the alarm is often supported by use of sound (Hollifield & Habibi, 2010). Different alarm priorities and categories are normally assigned different sounds, which should be appropriate for their level of urgency. Furthermore, the number of alarms in a process control room may be high, so inappropriate sounds may have a negative impact on perceived stress and concentration ability of operators.

Alarm management refers to the processes and practices for determining, documenting, designing, monitoring, and maintaining alarm messages from process automation and safety systems (Metah & Reddy, 2015, p. 569). In reality, alarm management does not always achieve this because they are improperly designed, poorly documented, changed without adequate review, or fail to provide enough information to the operator (Mehta & Reddy, 2015). An effective alarm system is a key part of a safe and reliable process. Incorrectly designed and poorly functioning alarm systems can have serious consequences and lead to ineffective alarm; which in turn leads to alarm flooding, nuisance alarms, high number of standing alarms, inadequate prioritization of alarms and improper or no alarm action (Mehta & Reddy, 2015)

An alarm system is a basic operator support system for managing abnormal situations, where the primary function of the alarm system is to warn the operator about a situation that is not normal (Norwegian Petroleum Directorate, 2001). The system should inform the operator about plant conditions that require timely assessment and possibly corrective action in order to maintain plant goals in terms of safety, productivity, environment and efficiency. Each alarm should alert, inform and guide the operator (EEMUA, 2007).

Auditory warning signals can improve performance and reduce accidents when they are employed successfully in the working environment (Edworthy, Loxley & Dennis, 1991). Safety threats, however trivial or seemingly unimportant, should not be ignored, especially in control room operations. The need for a standardized auditory alarm system for control room operations is done to migrate risk and eliminate safety threats to personnel onboard these installations. Confusion that arises due to different types of warnings could have damaging consequences if they are not redressed. Therefore, the cost of developing a redesigned set of alarms is negligible to the damaging consequences it may cause to personnel and property by ignoring it (Chowdhury, 2016, p. 168).

## *1.2 Project Background*

The inspiration for this thesis comes from a challenge at the international energy company, Equinor. The challenge at hand is that they don’t have a standardized set of auditory alarm sounds, leading to a variety of different sounds used at different on- and offshore process control rooms. This could create confusion among crew members who work on different rigs and installations. A solution to this, the company hired a music researcher, who has developed different types of alarm sounds for differing categories of control room alarms. These sounds are based on Equinor´s technical requirements (TR1494) for alarm systems, established principles for urgency scaling, as well as simplified user-centered design process. However, these newly developed alarms require testing on operators in order to narrow down which ones should be further developed and implemented in their control rooms. Due to the restrictions of COVID, an experimental method for data collection from operators was not possible to do in practice. Therefore, a systematic literature review will be performed to investigate currently existing methodologies in the scientific literature for auditory alarm development. Differing standards and guidelines related to auditory alarm development in the process industry, specifically, the Norwegian continental shelf will also be discussed more in depth.

## *1.3 Thesis Goals*

The overall goal of this research is to provide input for both process companies and auditory alarm designers for future development on auditory alarms. The research will be based on theories in human factors and design methodologies on the topic of auditory alarms. The objective of this study will be to do a literature review of alarm design methodologies for the process industry in order to provide inputs to different industry partners. There are known principles of design and cognition that might form the basis of auditory alarms intended for control room operators (CROPs), and this will be featured more in depth in background and related research.

The following are the research questions which have formulated based on the objectives of this research:

RQ1: *"What type of design process/methodology have been used for making a set of auditory alarms intended for the process industry?"*

RQ2: *"What type of characteristics should be specified for auditory alarms intended for the process industry?*

The thesis will be focused on a systematic literature review of previous peer-reviewed papers on the design and characteristics of auditory alarms in the process industry. This is done in order to guide and provide input into the most suitable methodology on auditory alarms from a research perspective.

# 2. Background

## *2.1 Alarm Management in the Norwegian Continental Shelf*

The concerns regarding alarm management in the Norwegian Continental shelf arose in the early 2000, after EEMUA-191 (1999) focused the worldwide attention to dangerous situations hidden within the alarm system's oil facilities (Villoria, 2013). This quickly became the de-facto standard to be used for alarm management in the industry. EEMUA-191 introduces for the first time considerations for human factors into alarm management, and asks the main question on what number of alarms can be effectively managed by a human operator.

In February 2001, the Norwegian Petroleum Directorate (OD) released the YA-711, the "Principles for Alarm Basis Design". This document is strongly based in EEMUA-191 which is considered a "Best Practice standard for development and operation of alarm systems for the British petroleum industry". Also released in 2001 was NORSOK I-002 Rev 2 (Safety and Automation Systems). This standard contains valuable guidelines regarding alarm design and management, and also gives Alarm and Event specific definition.

The YA-711 report gives a detailed philosophic guideline on the functional requirements of alarm system purpose, requirements, generation, structuring, prioritization, presentation and handling.

| |
|---|
| 1. The alarm system shall be explicitly designed to take account of human factors and limitations. |
| 2. The alarm system should be context sensitive. |
| 3. Operators shall receive instruction and systematic training in all realistic operational usage of the alarm system. |
| 4. The alarm system design shall be based on an alarm philosophy. |
| 5. The alarm system shall be properly documented, and clear roles and responsibilities shall be established for maintaining and improving the system. |

| | |
|---|---|
| 6. | It should be easy for process experts to build into and maintain knowledge and intelligence in the alarm system over time. |
| 7. | Performance requirements to the alarm system should be defined. |
| 8. | There should be an administrative system for handling access control and documentation of changes made to the alarm system. |
| 9. | The alarm system shall be fault tolerant. |
| 10. | System response time shall not exceed 2 seconds. |
| 11. | Safety critical functions should be identified and documented. Status information and failure alarms from these functions should be clearly presented and continuously visible on dedicated displays. |
| 12. | Status information related to safety system functions, such as blocking/inhibit and override, shall be easily available on dedicated lists and in process displays. |

**Table 1:** YA-711 2.2. General requirements

## *2.2 Practical Alarm Management at Offshore Control Rooms*

Alarm management at offshore installation uses the mentioned international standards and guidance in creating a set of alarms at each of their installations. Some oil companies have created their own standards based, like Equinor's own standard for alarm systems (technical requirement), called TR1494. The Petroleum Safety Authority Norway (PSA) was created in 2004, and has the regulatory responsibility for safety, emerging preparedness, and the working environment in petroleum activities (Norwegian Energy Partners, 2021). PSA has supervision on offshore platforms to make sure that oil companies follow these standards, and releases supervision reports on alarm loads and human factors on different control rooms in petroleum activities. The aim of these audits are to investigate whether the alarm systems at the control room provides panel operators with the necessary support in the handling of the process plant during normal operating situations, disruption and in the event of incidents. These are measured against relevant company and government requirements.

Examples of these supervision reports are on the platform, Mongstad base, owned by then Statoil (Equinor), where an audit was made in 2016 where they found three deviations from the regulations connected to (Petroleumstilsynet, 2016):

- Alarm load for operators in the control room
- Surveys of psychosocial conditions and human factors (HF) in the control rooms
- Noise conditions in the control room

A year later in 2017, following the previous audit, Statoil had initiated an alarm rationalization project that expects to make a positive contribution to a systematic review of the alarms (Petroleumstilsynet, 2017). The goal of the project is to reduce the alarm load significantly from the current level, increase attention to the most important alarms and comply with the performance requirements of TR1494 with a minimum of local adaptations. The impression from PSA is that the alarm rationalization project will contribute positively to a systematic review of the alarms. At the same time, it will be a good starting point for reaching their project goal of significantly reducing the alarm load from the current level, and securing Central Control Room (CCR) operators better overview and increased attention to the main alarms. This could probably contribute to increased operational availability at the plant as Statoil assumes. It was at the time of the audit, it has not been finally clarified which resources in the Statoil organization will be used to participate in the project. Finally, they emphasized the importance of freeing up resources for end-users (operators), so that representatives of these can actively participate in the project.

The supervision report brings up that the alarm systems on offshore control rooms are not always followed up in regards to the standards and guidelines set by the company and the government, but audits from the PSA contribute to companies starting alarm rationalization projects if there are found deficiencies in their current systems. Chowdhury (2016) states that some of the reasons for variation in alarm systems at various offshore installation are mainly due to two things:

- Different manufactures and vendors has constructed and supplied the various offshore installations at different points in time
- The standard or exact specifications for alarm system, indicators and code of signals are not specified by the companies to the manufacturers or contractors.

As a result, different contractors have installed different codes of signals and alarm systems as per their choice, convenience, and availability. This will leave an environment filled with inconsistent, confusing, meaningless, and often annoying alarm sounds (Wolfman, Miller & Volanth, 1996).

## *2.3 Auditory Alarms in the context of control room operations and warning systems*

The Engineering Equipment and Materials Users' Association (EEMUA) guide to alarms systems EEMUA 191:2007 (EEMUA, 2007, as cited in Stanton, Salmon, Jenkins & Walker, 2010, p. 293) provides a comprehensive description of the many factors influencing the design of an alarm system. EEMUA 191:2007 points out that alarm systems should:

- Be relevant to the operator's role at the time
- Indicate clearly what response is required
- Be presented at a rate that the operator can deal with
- Be easy to understand.

Essentially, alarms exist to alert the operator to a change of condition in the system (Stanton et al., 2010). If these are unattended, the changes may result in either a safety-critical situation or a non-optimal system. The main role of an alarm system are:

- Alert the operator that system has moved to a non-normal state
- Provide data and assistance to aid the operator in maintaining or returning to the optimal state.

In the work environment of a control room operator, the main task of an alarm is to distract the operator from his main task and induce a shift of his attention to the warning signal without being too disturbed (Guillaume, 2002). There are two kinds of information that are involved in hearing an alarm:

- Information about the real degree of urgency which may be conveyed by modulations in the acoustic properties of alarms

- Information about the cause of dysfunction that has unlocked the alarm by using adapted auditory icons.

A well-adapted warning sound increases the probability of an efficient reaction of the operator and then it decreases the reaction time. Therefore, too many different alarms are not optimal. The design of the alarm system has a significant effect on the performance of the operator. A well-designed alarm system considers the operators ability to recognize the situation, diagnose the fault, and develop a suitable course of action (Stanton, 1994). According to Edworthy & Stanton (1995), in practical design and standardization work, one is often confronted with the opinion that the warning sound, or set of warnings proposed, could somehow be improved upon and that some other sound or set of sounds would perform the function more effectively.

The EEMUA 191:2007 offers eight characteristics of a good alarm:

- *Relevant* – Not spurious or of low operational value
- *Unique* – Not duplicating another alarm
- *Timely* – Not long before any response is needed or it is too late to do anything
- *Prioritized* – Indicative of the importance of the operator dealing with the problem
- *Understandable* – Clear and easy to understand
- *Diagnostic* – Identifies the problem that has occurred
- *Advisory* – Indicative of action to be taken
- *Focusing* – Draws attention to the most important issues

Alarm prioritization is that the operator is able to distinguish the most important alarms to attend to. Human operators are limited by both their cognitive processing abilities and the physical response time to the number of alarms they can respond to in any given time (Stanton et al., 2010). As per International Maritime Organization (IMO, 2009) definitions, there are mainly four types of alarms based on priorities in control room operations, namely, (1) emergency alarm, (2) alarm, (3) warning, and (4) caution. The Emergency alarm indicates immediate danger to human life or to machinery requiring immediate attention and action.

Alarm is a high-priority alert requiring immediate attention and action. Warning requires no immediate action and is presented for precautionary reasons. Caution is a low-priority alert for awareness of ordinary consideration. Stanton (2010) states that there are two main factors to affect the prioritization of alarms: (1) the severity of the consequences that the operator could avoid by taking the corrective action, and (2) the time available compared with the time needed.

## *2.4 Alarm Philosophy*

All industries have goals for their operation and recognized limitations as to what they can accomplish. The alarm philosophy will recognize both and incorporate them into the alarm improvement process. (Rothenberg, 2009, p. 32) An *Alarm Philosophy* is a comprehensive guideline for the development, implementation, and modification of alarms (Hollifield & Habibi, 2010, p. 7). Basically, it is an instruction for implementing and handling alarms in the correct way. It is designed to optimize the definition and selection of alarms, their priority and their configuration. These will in turn minimize the total number of alarms, alarm duplication, noise and confusion. The alarm philosophy document is the first phase of the Alarm Management Lifecycle (Figure 1.) included in the standard ISA-18.2, and it is the basis for the entire framework.

This document will be useful in covering the entire range of alarm topics. It will reflect a full understanding of the alarm problem and the proper practices to follow. One can think of “alarm philosophy,” or alarm management philosophy, as a one-to-one synonym for a “complete design basis of an alarm system.” (Hollifield & Habibi, 2010, p. 567). All site personnel, all contractors, and all consultants will rely on it. Incident investigations will use it. (Rothenberg, 2009, p. 178). This gives the alarm designers a fully designed specification and guidance, which are necessary to produce new alarms.

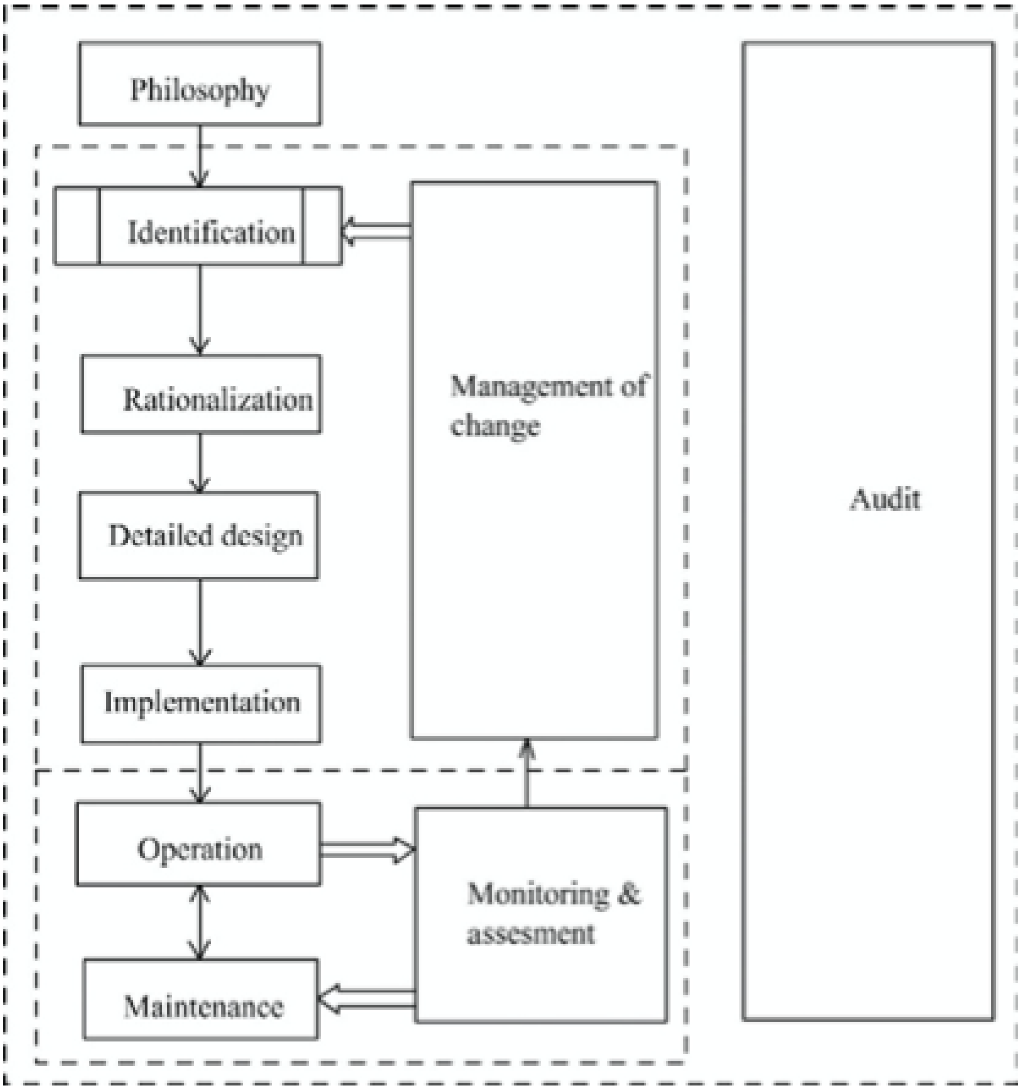


**Figure 1:** Alarm Management Lifecycle (ISA 18.2)

## *2.5 Human Factor Considerations*

The human factors will explain the flow of how operators respond to hearing an alarm, and that will be dependent on a number of factors. Operators responding to familiar auditory alarms will react in a very different way to operators encountering the alarm for the first time. The operator's response to hearing an alarm can be considered by using decision-making theory. Reason (1990) created a flowchart (Figure 2.), based on the research of Rasmussen (1974) to describe a process categorizing decision making into rule- and knowledge-based behavioral levels. Rule-based decision making is fast, whereas knowledge-based decision making is slow and effortful. The time taken by operators to respond to an alarm will therefore be heavily influenced by their familiarity with the alert and their ability to associate this with a plan of action (Stanton et al., 2010, p. 298).

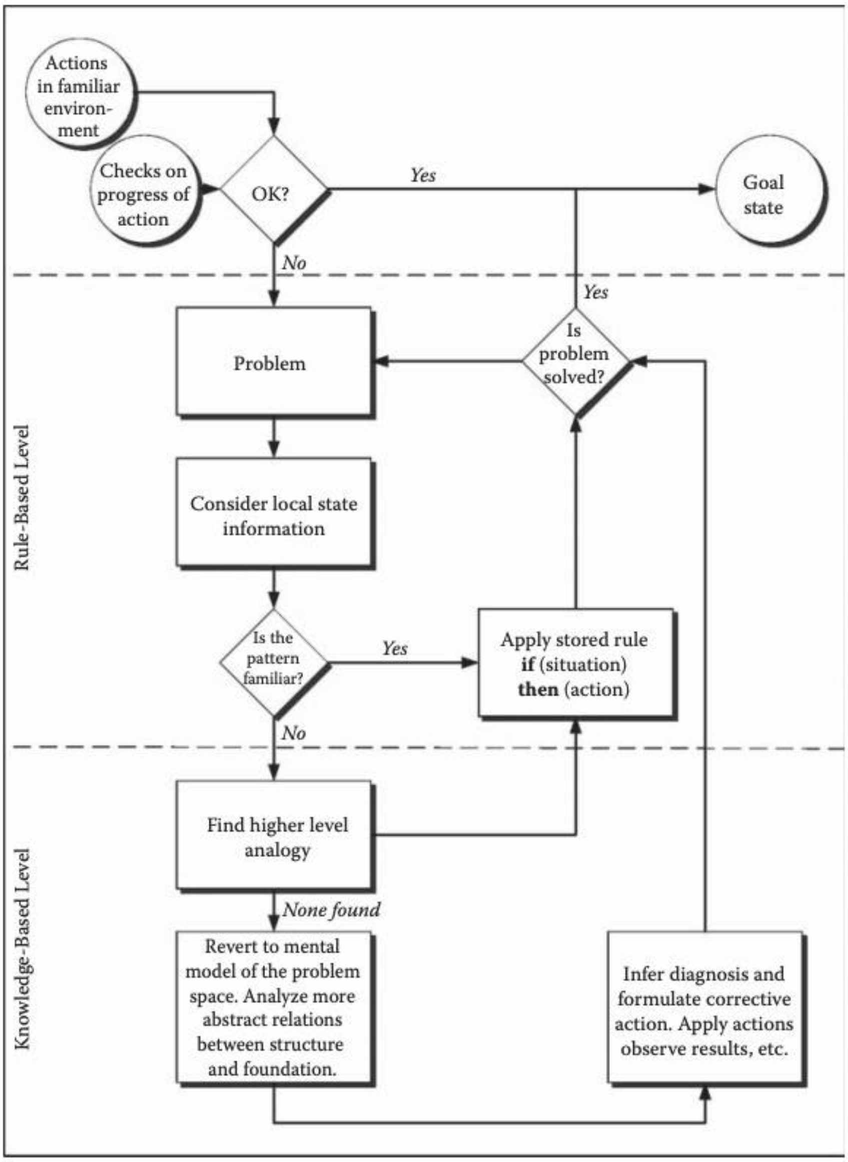


**Figure 2**: GEMS Framework (Reason, 1990)

The development of auditory alarm systems should be able to support both rule-based and knowledge-based behavior. During the rule-based decision making, operators should have the ability to short-cut the response process to allow them to act upon previous experience and mental models. To support the operator in knowledge-based behavior, the system should provide the operator with suggested causes for the situation, as well as information on higher order effects of any action taken to return the system to a desired state (Stanton et al., 2010).

Patterson (1990) proposed to create an alarm that allows the listeners to think, communicate and react efficiently to them, without being dominated with the idea of turning the alarm off. This is done to the perception of urgency that the operator feels when hearing the alarm. In the estimation of urgency, the intensity level plays a major role, where the louder the warning signal is, the greater the urgency estimation. Perceived urgency of alarms may affect the operator since the warning could be perceived as too urgent or not urgent enough and this may affect compliance and prioritizations made by the operator. An evaluation of urgency can be made even when the listener does not know what the warning means, because urgency is a function of the mix of acoustic parameters and the intensity in a warning (Ulfvengren, 2003).

System designers often fail to consider the limitations of the human operator when specifying auditory warning signals, thereby compromising their effectiveness. For example, some systems rely on an excessive number of auditory alarms presented at unreasonably high volumes, often occurring simultaneously (Belz, Robinson & Casali, 1999).

## *2.6 Previous research on user-centered design for auditory warnings*

To create a user-centered design process for auditory alarms it is important that the end-user (operators) are included in the whole process. Professor Judy Edworthy has done much research on auditory alarms over the past 30 years, mainly in the field of hospital alarms. The main estimation ratings found in most alarm testing methods was to find the subjective ratings of perceived urgency, appropriateness, annoyance and response time to the sounds. Results from these studies and methodologies can be used as an insight for the design of auditory alarms which needs to convey a sense of urgency.

The design and implementations of warning sounds in critical situations has been discussed for many years. Patterson and Mayfield (1990) and Edworthy et al. (2017) elaborated criteria concerning the attributes of warning sounds in order to distinguish them from the production environment. They mention “alarm fatigue,” “alarm flooding,” as aspects needing to be considered for the design of warning sounds. The avoidance of too many sounds, i.e., also of too much information to be handled properly (Hearst, 1997), appears to be as important as the prevention of inattentional deafness, i.e., the failure of noticing warning sounds (Chamberland, Hodgetts, Ballieres, Vachon & Tremblay, 2017). Most implementations of alarming sounds are based on intermittent, event-based auditory displays presenting one or a sequence of sounds, either in anticipation of, or on the actual occurrence of critical situations (Watson, 2006).

A study conducted by Edworthy & Stanton (1995) presents a method on an user-centered approach to the design and evaluation of auditory alarms. Their procedure is essentially an user-centered approach, where they capitalize upon the users' association between the alarm sounds and their meaning. The procedure is presented in a step-by-step manner, from the indication of referents for which warnings might be required, through the generation of ideas for warning sounds, an appropriateness ranking test, a learning and confusion test, an urgency mapping test, recognition test and finally an operational test. The practical issues are discussed at each of the stages of the procedure, and suggestions are made to courses of actions if problems are encountered. They call it the urgency mapping principle, which has been a big inspiration to other researchers when creating a set of auditory alarms, given that one can manipulate sound parameters in order to produce urgency contrast. (Edworthy et al., 1991; Hellier et al., 1993; summarized in Edworthy, 1995). How urgent a warning is perceived often gives the user an indication of how quickly a response is required.

An experiment by Haas & Edworthy (1996) used two dependent measures: estimation rating of signal urgency, and participant response time to the warning signals. This experiment provides a detailed, testable description of the dependence of perceived urgency and response time of auditory warning signals. A study on the design of natural warning sounds by Ulfvengren (2007), suggests that human errors are often the consequences of actions brought by poor design. In alerting situations with auditory alerting systems, both disturbances and annoyance of alert may affect the performance, especially in non-normal situations when the mental workload is high. Sounds that are appropriate as auditory alert should either have a natural meaning within the user's context, or that they are compatible with the human's natural auditory information process. The conclusion states that they could be both of these cases, where the auditory alarm is not *annoying*, *easy to learn* and *clearly audible*.

The research of Marshall, Lee & Austria (2007) provides a great insight of the influence of the auditory characteristics of alert on perceived urgency and annoyance. Based on the foundation of urgency mapping by Edworthy (1995), and the parameters of annoyance associated with environmental noise. The result of this study shows that there is a strong relationship between perceived urgency and rated appropriateness for auditory alerts, and that sound parameters differentially affect annoyance and urgency. In the design of auditory warnings, the parameter of annoyance may merit as much attention as urgency.

The final research article on the development and selection of auditory warnings by Bellettiere et al. (2014) used a four step process in their development, testing and selection of auditory warnings. Their survey was designed to measure the relative aversiveness of each auditory warning, determine the participants' reported behavioral reaction to the warning and the participants preference for priority they were in. Their four-step process for selecting the appropriate alarms was based on and similar to Edworthy and Stanton's (1995) 10-step user-centered approach on designing auditory alarms. This approach involves representatives of the indented users in an effort to arrive at signals that are effective, tolerable and fit within the user environment.

## *2.7 Alarm Standards*

A selection of the different standards found in the process industry will be compared in regards to their guidelines on the topic of alarm systems. The selected standards are the ones commonly used in the offshore industry, including YA-711, which are mandatory for petroleum production facilities in the Norwegian continental shelf, and also TR1494, which is mandatory on a company level for Equinor.

**EEMUA 191**

Alarm Systems—A Guide to Design, Management and Procurement. This Engineering Equipment and Material Users Association (EEMUA) guide emphasizes human factors in the design of alarm systems.

**NORSOK I-002**

The NORSOK standards are developed by the Norwegian petroleum industry. This standard covers functional and technical requirements and establishes a basis for engineering related to Safety and Automation System Design. (NORSOK STANDARD, 2001)

**ISA 18.2**

Management of Alarm Systems for the Process Industries. The International Society of Automation (ISA) is an American association that sets the standards for automation and control systems used by industry.

**YA-711**

Principles for Alarm System Design, published by the PSA. This covers basic principles and philosophic guidelines on alarm generation, structuring, prioritization, and presentation for offshore installations on the Norwegian Continental Shelf.

**TR1494**

The objective of these documents is to provide the framework of the technical and operational requirements and standards to be applied for the alarm functionality. It will outline the set of rules to be followed with respect to human factors, generation, structuring, documentation, prioritization and presentation of alarms. This TR is valid for the Safety Automation System (SAS).

# 3. Methods

## *3.1 General introduction*

This study has been undertaken as a Systematic Literature Review (SLR) based on the guideline from Kitchenham (2004). A SLR is a method of identifying, evaluating and interpreting available research relevant to a particular research question or topic area (Kitchenham 2004). Systematic reviews provide objective summaries of what has been written and found out about research topics. This is especially valuable in wide research areas, where many publications exist, each focusing on a narrow aspect of the field (Budgen & Bereton, 2006). Systematic literature reviews differ fundamentally from traditional ones. Rousseau, Manning & Denyer (2008, p. 476) state that the main difference lies in their representativeness: while traditional reviews tend to be “cherry picking studies”, systematic reviews aim to provide a full overview of research conducted on a specific field until the present date. All research procedures have to be made explicit before the actual conduct of the review to make the process objective and replicable.

The main advantage of SLR compared to a normal research review is that it provides a higher degree of confidence about covering the relevant literature, and thus minimizes the subjectivity and bias through reproducible results (Kitchenham et al., 2010). Individual studies that contribute to a systematic review are called primary studies. A systematic review is a form of secondary study.

There are three main reasons for performing a systematic literature review (Kitchenham and Charters 2007).

- To gather and evaluate all existing evidence of a research topic in a rigorous and systematic way
- To identify gaps in current research in order to suggest areas for further improvement
- To summarize and provide background for performing new research activities

The following sub-sections detail the methodology of the SLR process implemented in this study, including the research questions, search strategy, inclusion/exclusion criteria and data extraction. Finally, there will be a review of the alarm system standards which are commonly used in the process industry.

## 3.2 Research design

### 3.2.1 Research Questions

The systematic review process consists of 3 stages: (1) Planning the review, (2) Conducting the review and (3) Reporting (Kitchenham 2004). The major differentiating factor of SLR over explorative reviews is the pre-defined protocol and research questions. Defining the scope of the review and answerable questions is an important first step of the SLR process. For defining the scope of the systematic search, the PICOC framework has been utilized (Booth et al. 2012).

RQ1: "What type of design process/methodology have been used for making a set of auditory alarms intended for the process industry?"

This question aims to identify how auditory alarms have been designed and adopted in different industries, specifically the process industry. The results will be useful for developing a framework for future auditory alarm design intended for the process industry.

RQ2: "What type of characteristics should be specified for auditory alarms intended for the process industry?"

| PICOC element | Definition |
|---|---|
| Population | CROPs in the process industry |
| Intervention | Optimizing user centered auditory warning sounds for control rooms |
| Comparison | Redesigned alarms vs. current alarms |
| Outcomes | Consistency and appropriateness of alarm sounds |
| Context | User-centered auditory alarms intended for process industry |

The aim of this question is to identify the properties of auditory warnings which are used to create a user-centered set of alarm sounds intended for operators in the process industry.

### *3.2.2 Search Process*

The search is conducted in four databases (Web of Science, Scopus, IEEE Explore and SAGE Journals). These databases are well-established, multi-disciplinary research platforms, holding a variety of peer-reviewed journals, and they are being kept up to date. The selection of these databases is to ensure relevant papers are included, since it is possible the one database omits relevant research. The literature search process was carried out in the months of March and April 2021.

The performed search in the above databases will use the following search sting. The search term for this review will combine the terms for auditory warnings/alarms and design/testing with the terms to include the control room and process industry.

(“Audi*” OR “Alarm”)
AND
(“Sound” OR “Warning” OR “Alert”)
AND
(“Design” OR “Test*” OR “Method*”)
AND
(“Control Room” OR “Offshore” OR “Process Industr*”)

### *3.2.3 Inclusion and Exclusion Criteria*

The inclusion and exclusion criteria for selecting the primary studies were specified according to the SLR methodology. The primary criteria for inclusion was that the studies used auditory alarms in the field of process industry applications. Considering the research question, in the general criteria, the time frame of the study and relevant type of study were defined.

General Criteria:

- Peer-reviewed studies published between January 1st, 1990 and March 31st, 2021.
- Studies that describe the applications and effectiveness of auditory alarms in a process industry setting.

Specific Criteria:

- Studies that focuses on auditory alarms in the field of process industry applications
- Studies that uses auditory alarms in their testing

- Studies that compare standards vs. user-centered design
- Studies that includes human factors in the design

Exclusion criteria:

- Studies that are not published in English
- Studies that were published before 1990
- Books, tutorials and poster publications
- Studies where auditory alarms is not the subject or focus
- Studies that are not related to/applied for the process industry

### *3.2.4 Data Collection and Extraction*

In the data collection and extraction phase of the review, the documents found in the searching phase were reduced to a final number of documents which were relevant for answering the research questions. Inclusion and Exclusion criteria were utilized to screen the documents further.

The data extracted for each article are:

- Bibliographic information of the publication
- The main research question of the study and outcomes
- The methodology used for measuring the outcome
- The population of the study
- The metrics used of measuring the alarms
- What are all the objectives/challenges addressed in the study

## 4. Results

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) defines a set of items to help authors improve the reporting of SLR (Mariano, Leite, Santos, Rocha & Melo-Minardi, 2017). Figure 3 presents the stepwise approach of reviewing and selecting the papers.

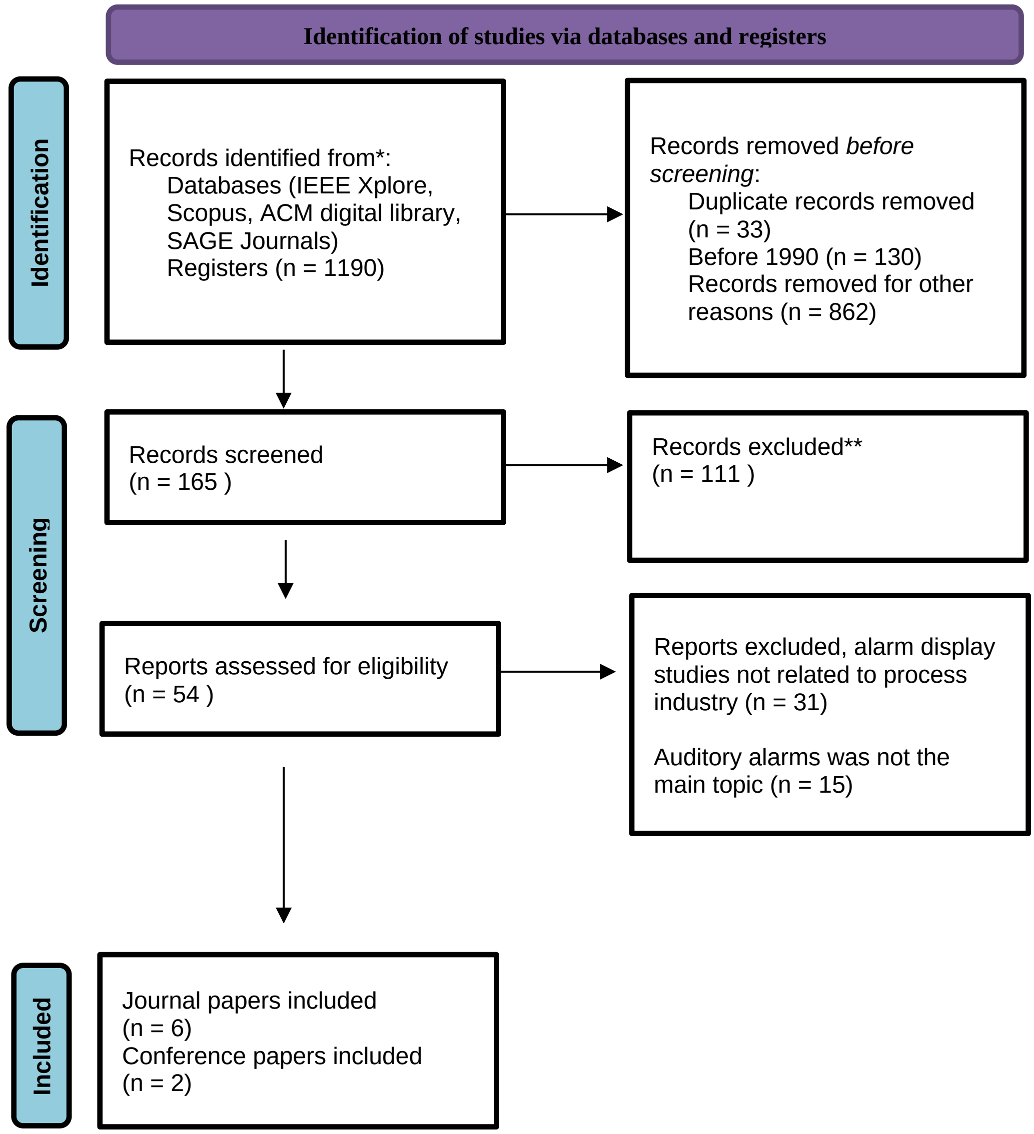


**Figure 3:** Results from the search and selection process (PRISMA flow diagram)

This section presents the results of the review, answering the two research questions based on the extracted data from 8 studies over a publication period of 30 years. The identified results were extracted to EndNote, where the screening of the collected literature could commence. The initial high number of hits from the search string was due to the fact that the databases of Sage Journals (n = 478) and IEEE Xplore (n = 407) gave the highest search results for papers regarding alarm systems in many different applications and contexts. The other two databases AMC digital library (n = 116) and Scopus (n = 189) gave a lower result. Papers involving alarm systems focusing only on visual search tasks with little to no regards to auditory displays were removed from the review. The search was further reduced to only the application of the design of auditory alarms to be used by the process industry. Documents that describe just the concept of alarms in other applications than the process industry were also removed. After the application of inclusion, exclusion and quality criteria, 8 studies were selected for the final data analysis. Overall, the results from the search were synthesized by extracting the main themes under which the findings of this review are identified and presented. The 8 studies included in the final data were analyzed in the following sub-sections based on the challenges of alarms, design of auditory alarms and their characteristics. The documents to be included in the final review are 6 journal papers and 2 conference papers. These papers are summarized in Table 2.

Many of the studies excluded from the final review were studies where the main subject was surrounding auditory alarms, but not directly connected to process industry application. These studies were assessed for eligibility, but excluded due to the inclusion criteria for the SLR.

## *4.1 RQ1: Auditory Alarm Design for the Process Industry*

The studies generally focused on improving alarm design for the end users. Six of the reviewed studies use established human factor research in their design for auditory alarms, while only four of the studies utilizes the EEMUA-191 as a guideline for the design (Bransby, 1999; Brown, 2003; Sirkka et al, 2014; Fagerlönn et al., 2017), where one of them also takes into considerations the IEC 61508 Standard (Bransby, 1999). The theory of urgency mapping from Edworthy (1991) is actively used in four of the studies (Johannsen, 2004; Reed & Strybel, 2004; Sirkka et al., 2014; Fagerlönn et al., 2017), where they focus on the perceived urgency of operators in assigning auditory alarms to their desired prioritization. Xiao & Seagull (1999) takes into consideration the framework established by Stanton (1994) and Rasmussen (1983) on the theory of knowledge-, rule- and skill-based behavior of operators when they are exposed to an alarm. The last study by Viraldo & Caldwell (2013) proposes using sonification in the design of alarms to more effectively convey the appropriate meaning

***Table 2**: Summary of Results with  SLR*

| Study | Title of paper | Population | Methodology | Objective/Challenge | Characteristic of alarm | Outcomes |
|---|---|---|---|---|---|---|
| Bransby (**1999**) | The Human Contribution to Safety: Designing Alarm Systems for Reliable Operator Performance | N/A | Review | Overview of major accidents of human errors in control room alarm systems | Based on alarm prioritization | Recommendation of EEMUA to assist industries users in achieving better alarm system performance, and importance of human factors due to human-system challenges contributing to major accidents |
| Xiao, & Seagull (**1999**). | An Analysis Of Problems With Auditory Alarms: Defining The Roles Of Alarms In Process Monitoring Task | N/A | Review | Review of reported observations and challenges between human operators and alarm mechanisms in patient care, aviation, and process control | Based on alarm prioritization | Roles of alarms in process monitoring tasks should be viewed more as a way of informing process status and less as a way of interpreting the significance of process status. Can best be understood in the skill-, rule-, and knowledge-based framework. Design of alarm devices should be guided by the principle of information provision regardless of whether an alarm may be true or false indication of “alarming” events |
| Brown (**2003**). | Alarm Management - The EEMUA Guidelines in Practice | N/A | Review | Overview of EEMUA guidelines and the issues of alarms and how significant improvements can be achieved. | Based on alarm prioritization | Pragmatic approach to alarm rationalization can realize significant improvements. |
| Johannsen (**2004**). | Auditory Displays in Human–Machine Interfaces | Nonmusicians (8), and professional musicians (2 | Three exploratory experimental studies: Understandability of directional sounds; Robot state sounds; Auditory perception | Compare different types of auditory displays, such as warning, state and intent displays | Urgency Expressiveness Annoyance | Shows  that the suggested auditory symbols and sound tracks are feasible means of communication in human–machine interaction |

**Table 2**: (continued)

| Study | Title of paper | Population | Methodology | Objective/Challenge | Characteristic of alarm | Outcomes |
|---|---|---|---|---|---|---|
| Reed & Strybel (**2004**). | Does The Perceived Urgency Of Auditory Signals Affect Auditory Spatial Cueing In Visual Search Tasks? | Students (5) | Investigation of auditory spatial cueing in visual search with auditory cues in different levels of perceived urgency | To understand is harmonicity and interpulse interval that affect perceived urgency of warning sounds would affect visual orienting in a visual search task | Informativeness and perceived urgency. | In paired-cue conditions, perceived urgency affect the amount of interference produced by uninformative cues. In highly-urgent informative cues, the urgency of the informative cue determined the amount of interference in visual search. In less-urgent informative cues, the effect of uninformative cue urgency was less clear, because they produced more interference than more urgent uninformative cues |
| Viraldo & Caldwell (**2013**). | Sonification as Sensemaking in Control Room Applications | N/A | Review | Introduction of sonification to different types of industries | Learnability | A technique to inform operators in a more understandable way could be the use of sonification to reduce alarm flooding and increase sensemaking of situational awareness among operators. |
| Sirkka et al. (**2014**). | An Auditory Display to Convey Urgency Information in Industrial Control Rooms | Control room operators (14) | Experimental design of two display concepts to be compared with two baseline displays | Test and evaluate four types of auditory displays | Perceived urgency Annoyance | The results show that one can design auditory displays that employ appropriate urgency mapping while the perceived annoyance is kept at a low level. Suggests involving the end users in the design process could be advantageous |
| Fagerlönn et al. (**2017**). | Designing a Multimodal Warning Display for an Industrial Control Room | Operators (17) | Experimental design on different auditory alarms, in different urgency levels, with three types of visual units | Develop a new type of multimodal display to enhance the effectiveness and acceptance of warnings in an industrial control room | Perceived Usefulness Perceived Satisfaction | Operators find it easier to identify the alarm section using a multimodal display |

of the sound to the user. Sonification is new to human factor research and has been successfully used in diverse fields including medicine, motion study, search and rescue operations, interactive entertainment and sports (Viraldo & Caldwel, 2013 p. 622).

When it comes to the assessment methodology, among the 8 reviewed studies four were user studies where the evaluation from the end-user were the metrics of assessment (Johannesen, 2004; Reed & Strybel, 2004; Sirkka et al., 2014; Fagerlönn et al., 2017). Two of the studies used operators in control rooms as participants (Sirkka et al., 2014; Fagerlönn et al., 2017), where one study used students (Reed & Strybel, 2004) and the last used musicians and nonmusicians (Johannesen, 2004). The user evaluation in these studies were generally positive in developing an auditory alarm sound intended for its purpose, where the study of Fagerlönn et al. (2017) evaluated the alarms both before implementation and six months after the first data collection. The study conducted by Sirkka et al. (2014) was the only one of the reviewed assessment methodology studies which designed their alarms in accordance with the EEMUA.

## *4.2 RQ2: Sound Characteristics for Auditory Alarms in the Process Industry*

All of the reviewed papers mention some form of characteristics that the alarm sounds should have when developing alarm systems for the end-users. Some of the studies state that the auditory alarms should be distinctively classified in different priorities (Bransby, 1999; Xiao & Seagull 1999; Brown, 2003). The mentioned urgency mapping based on the research the research by Edworthy et al. (1991) has been an inspiration to four of the studies in the focus of characteristics of alarms (Johannsen, 2004; Reed & Strybel, 2004; Sirkka et al., 2014; Fagerlönn et al., 2017). This is due to the fact that perceived urgency from incoming sounds are effective in prioritization of incoming information. To use prioritization effectively, high priority should be reserved for those alarms where the consequences of the operator failing to respond appropriately are greatest, which means that designers should only select certain alarms to be implemented as safety related (Brown, 2003). Reed & Strybel (2004) focused in their paper on auditory cues of different levels of perceived urgency to investigate the spatial cueing in visual search with auditory cues. In addition, the study of Sirkka et al. (2014) wanted to investigate how reliably operators could identify three different levels of urgency (low, medium, high). The same goes for the annoyance (Johannsen, 2004; Sirkka et al., 2014), where it is an important characteristic to consider when implementing auditory warnings in user context, where operators may try to avoid experiencing the negative emotions associated with the sound simply by avoiding the sound (Sirkka et al., 2014). Other characteristics from the reviewed papers that are taken into account for designing auditory alarms are: Effectiveness (Fagerlönn et al. 2017), Usefulness (Fagerlönn et al. 2017); Expressiveness (Johannsen, 2004); Distinctiveness (Sirkka et al., 2014); Informativeness (Reed & Strybel, 2004) and Learnability (Viraldo & Caldwell, 2013). Manipulating audio data is done by changing pitch, tone, amplitude, loudness, and tempo of audio signals in order to maximize their effectiveness for use in audible alarm systems. (Viraldo & Caldwell, 2013).

### *4.3 Human Factors Considerations*

The literature pinpoints that the human factors are one of the most important features in the design of an auditory alarm, where it is the end-user who will be around the alarms on a daily basis. With the lack of understanding of what kind of information auditory warnings provide, the design is driven often if not mostly by what is technically possible and by legal concern, rather than by the requirement for providing relevant and timely information to human operators (Xiao & Seagull, 1999). Human errors can be classified on different cognitive levels in alarm systems, on the three levels of skill-based, rule-based, and knowledge-based behaviors (Xiao & Seagull, 1999; Johannsen, 2004). Errors at the skill-based level consist of slips and lapses, whereas errors or mistakes at the rule-based level may be divided into the misapplication of good rules and the application of bad rules. Finally, errors or mistakes at the knowledge-based level originate from bounded rationality or an incomplete or inaccurate mental model of the problem space (Johannsen, 2004, p. 747).

Johannesen (2004) states that there are two important characteristics to be achieved in well-designed alarm systems, and those are human centeredness and task orientation. Human centeredness emphasizes the individual differences between users and hence the importance of user modeling. It also stresses that the views of designers and users may be different, and the designer must take this into account. Task orientation is where the final objective of a human-machine interaction is the accomplishment of a number of tasks. Both these tasks can be achieved with the participation of end users in early stages of the design, and other forms of user participation during later stages of the design process consider the evaluations of intermediate prototypes and of the final interface product itself (Johannesen, 2004, p.748-749).

## 5. Discussion

The purpose of this review was to help identify the relevant literature on design in the process control industries. To answer the first research question, the literature provides an understanding on what has been done when designing auditory alarms in respect to auditory literature, and mainly the use of standards like the EEMUA-191. Many of the articles are using more of an auditory design methodology from previous research from the likes of Edworthy (1991) and Stanton (1994), rather than the guidelines and international standards, like the EEMUA-191, and others provide. These proposed methodologies came out some time before the different guidelines were being used by the processing industries, where they provide more of an insight into specific human factors considerations in the design and evaluation of auditory alarms. These methodologies give the designer more of a direction on what auditory characteristics affect humans to perceive a sound that indicates what is urgent and should be prioritized. As stated in the background chapter, from the first of the YA-711 guideline on general requirements of alarms: "Alarm systems shall be explicitly designed to take account of human factors and limitations". What is meant by this is that designers shall ensure that the alarm system remains usable in all process conditions, by ensuring that unacceptable demands are not placed on operators by exceeding their perceptual and cognitive capabilities.

To answer the second research question was to find in the literature what types of characteristics in the alarm sounds that researchers have specified as the most important. The research of Bransby (1999) and Brown (2003) explains the main design methodology of alarms using the EEMUA guidelines is that the alarms mee the operators needs and functions within the operator's capabilities, and that they should be able to distinguish the different alarms by prioritization. The design of auditory alarms using the different standards and guidelines gives little to no instruction on what the auditory alarms should sound like to be distinguishable in different priorities, or what characteristics should be the focus for designers when creating an alarm. A significant body of literature was found that addressed the question of challenges with alarms today and the use of ergonomics and human factor information by engineering designers/design engineers.

## *5.1 Challenges with alarms today*

"Before we can solve a problem, we need to know exactly what the problem is" (Dolfing, 2018). An alarm management challenge is to control nuisance alarms, alarm floods, alarms with wrong priority, and redundant alarms. Poor alarm system performance is one of the main issues implicated in numerous serious industry accidents (Bransby, 1999; Brown, 2003). In the reviewed studies, there were a number of reasons why there was a need for industries to do something about the current alarm systems (Appendix A). The most common problems with alarms found in the literature was:

| Alarm Issues | |
|---|---|
| Brown**, 2003;** Johannsen**, 2004;** Reed & Strybel; **2004;** Viraldo & Caldwell**, 2013;** Sirkka et al**., 2014** | Alarm Flooding |
| Viraldo & Caldwell**, 2013** | Alarm Fatigue |
| Brown**, 2003** | Standing Alarms |
| Xiao & Seagull **1999** | False Alarms |
| Brown**, 2003;** Xiao & Seagull**, 1999** | Nuisance Alarms |
| Bransby**, 1999** | Poor Alarm Performance |
| Xiao & Seagull**, 1999** | Inopportune Alarms |
| Fagerlönn et al**., 2017** | Inadequate Priority Rating |
| Bransby**, 1999;** Fagerlönn et al., **2017** | Learnability of Alarms |

**Table 3:** Results of challenges with alarms from SLR.

These different conditions of the alarm system are a problem for the end-users, where it results in cognitive loads and stress, and leads to degraded performance (Viraldo & Caldwell, 2013). Alarm flooding, or too many alarms of a single operator to be physically addressed, are the main challenge mentioned in most of the literature. Nuisance alarms or "wrong context" alarms, are alarms sometimes labeled as false alarms due to their perceived absence of value to human operators (Xiao & Seagull, 1999; Brown, 2003). Nuisance alarms are those indicating state changes that are potentially dangerous to system integrity in some context, but not in the context in which they are set off. These problems with alarms today become more as challenges to solve for the sound designer to create effective warning sounds.

The study of Xiao and Seagull (1999) analyses the problems with auditory alarms, where they discuss the main impact of these challenges and reviews literature surrounding the human factors considerations in the design. Their conclusions are that designers of alarm systems should focus more on the concept of information provision, rather than the only performance function of alarms, which is to alert.

## *5.2 Recommendations for design of Auditory Alarms*

Decisions should be made within the framework of an overall design strategy and philosophy which should include a formal set of principles and policies for alarms (Brown, 2003). Warnings in different user contexts and situations demand different types of responses (Sirkka et al., 2014). This makes it challenging to design a specified set of alarms to be used across an organization, where different installations and operations are not similar to each other. In the case of homogeneous industries, a similar design methodology can be used across the organization, where an operator can travel between installations and know the exact meaning of the auditory alarms he/she hears. Urgent situations occur in a complex control room environment, where it is essential that the operator remains focused in solving a problem. The designers should attempt to find solutions that inform and guide the operator effectively and reliably while minimizing annoyance and disturbance, although this could become a challenge for the designer.

Sirkka et al. (2014) used a user-centered design process based on previous research results to find the solutions that are the most appropriate in their design. This provides the designers an understanding of the different parameters that influence urgency and annoyance in alarm sounds. In addition, operators contribute to the design with their own knowledge regarding their work context, i.e. the type of urgent situations that can occur, and what tasks that need to be performed. This additional insight can assist designers in adapting the sounds to make them more suitable and tolerable in the actual work context. Some limitations come from a user-centered design of auditory alarms, where Fagerlönn et al. (2017) states that the user involvement may contribute to more positive scores in the design and selection of new alarms. First, since the operators know what works well for them, they contribute to a more appropriate auditory sound that suits them. Second, participation may have made operators rate the designed solutions more positively (Fagerlönn et al., 2017).

## *5.3 Main Considerations of Characteristics in Auditory Alarms*

Some of the issues regarding auditory alarm systems today are the inadequate priority rating, where the users find the alarms too urgent or not urgent enough. It should be noted that the characteristics of auditory alarms are subjective ratings by users, where one might find a sound more annoying or urgent than the next. Both Sirkka et al. (2014) and Fagerlönn et al. (2017) concluded in their studies that by keeping the perceived urgency high, and perceived annoyance low of operators, the sound signal will be more effective and less annoying characteristics will be more tolerable.

Priority will be used by the operator to do one single task—decide the importance of alarms (Rothenberg, 2009). As mentioned earlier, appropriate urgency mapping is preferable in the design of auditory warning, where it can help operators prioritize new information and minimize confusion. An inappropriate mapping could have the opposite effect on operators and potentially increase the workload. As stated by Sirkka et al., (2014): “All warnings in the operators’ environment must be considered according to the urgency mapping principle in the design process”. They used this approach in accordance with the EEMUA-191, which states that an integrated design should be developed for all auditory warnings in and that the operators’ ability to identify the priority of the alarms is desirable. Also, by manipulating parameters such as speed and frequency, the designer can systematically change the perceived urgency of the sound.

## *5.4 Purpose and Scope of Standards in Relations to Reviewed Papers*

Most of the standards intended for the process industry are based on the EEMUA-191, and there is an understanding that they are very general, and intentionally describe the minimum acceptable criteria for an effective alarm system, and not the optimum.
The existing standards and guidelines say little of how to accomplish the recommended design of appropriate sounds and their presentation format, which may be one reason why so few of these guidelines are applied in previous research on auditory alarms. The main consideration found in the different standards are that the auditory alarms should be based on the priority setting of the alarm philosophy. This shall in turn give the operator an indication on the importance of the audible alarm.

By design, the standards have more of a focus on *what to do* rather than *how to do it*. They do not provide specific examples of proven methodology or detailed practice, where standards focus more on requirements (“shall”) and recommendations (“should”) for an effective alarm management (Hollifield & Habibi, 2010, p. 184). This becomes a challenge for designers, where the standards provide mostly little indications on the auditory part of an alarm, but more on how the alarms should be prioritized and presented. The standards give the sound designers an idea of what the end-results of an effective alarm system should be, but not on how to achieve it. Only one study from the results mentions that they took the EEMUA-191 into consideration when designing the alarms. This is of course different for industry to industry, where control rooms in aviation, hospitals etc. use different standards than the ones mentioned in this thesis. There is no specific evidence that there is a gap between alarm-related standards and how the standards are translated into practice, but process industries should be using standards in their consideration when designing auditory alarms. There is much room for improvements in auditory alarm systems, and more research is needed to develop guidelines and methods for a user-centered design of appropriate alarms and their presentation for future alarm systems.

## *5.5 Limitations*

This study is not without limitations, where it is not a detailed thesis on how the different parameters of auditory sounds should be for the process industry, but more a look into what methodologies have been used in this industry.

The reliability of conducting a SLR is high, where the definition of the process in the methods chapter is clearly and specifically defined in such a way that it will guide the review process (UKEssays, 2018).  The process definintion of the SLR is created to include as much details as possible to avoid the bias.

The primary search in the SLR gave the eight papers that have been used in this thesis, where these are four primary studies and four reviews in the context of auditory alarms in the process industry. These results could be considered as low, where a possible solution could have been to use other databases. In return, this also questions the validity of the results found in the SLR. A possibility for the low result on finding papers on auditory alarms in the process industry could be that most of the research done in the industry has been completed internally and not published in public domain, most likely because of the confidentiality in the differing companies. It would be interesting to see research how different process industries have used different methodology in the process of creating and designing different auditory warnings, or if they have used the same with the same or different outcomes.. This thesis shows a reliable result through conducting a SLR, but

Finally, although the alarm-related standards are the most common ones used by alarm manufacturers in the process industry, the study did not include any other alarm standards, which may limit the findings of this thesis.

### *5.6 Recommendations and Further Research*

An auditory design procedure has been made to take account of the different processes that should be included when designing an auditory alarm intended for the process industry, represented in figure 4. This model is based on the diagrammatic representation of design procedure by Edworthy & Stanton (1995), but it has been modified to the combination of results found from the peer-reviewed papers in the SLR and differing standards in the process industry. This model could be valuable to stakeholders and provide input for future development and research on this area, as this simplified figure shows the process (left-hand side) of the design of auditory alarms, and the description (right-hand side) to give a clear understanding of each stage.

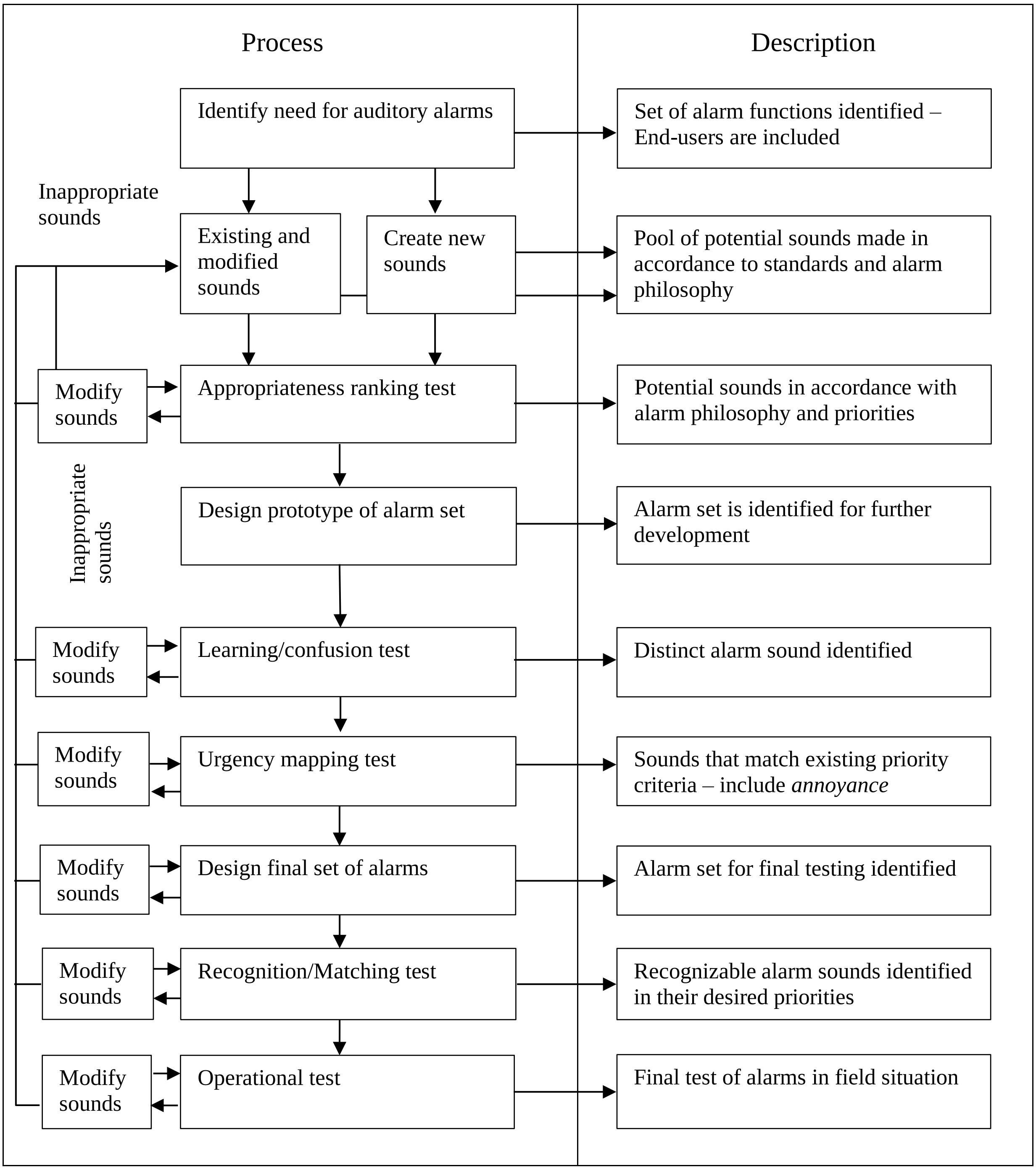


**Figure 4:** Representation of auditory alarm design procedure for process industry

This method takes into account the documented standards and alarm philosophy to be the basis for auditory alarm design, where the operators are included through the whole process of the auditory alarms design. The important procedure of this method is the modification of sounds, where the sounds are in accordance with the standards and would be perceived as suitable by the designer, but are clearly not liked by the operator. The sounds should be easily modified by the designer when the feedback from operators gives an indication that they don't like the suggested sounds for the auditory alarms. This could be a challenge for the sound designer, where too many modifications can give the sound property a misdirection from the intended standard it is based on.

There has been a good amount of research done in the past on auditory alarms for different control room applications, but there is not a lot in the field of the offshore process industry. This thesis can be used as a simplified guide of the design of auditory alarms both for use in the process industry, but also for other control room applications. Further research on this topic would be on the improvement effects of implementing new/redesigned auditory alarm systems, in relation to the standards set by the industry today. Further design and experimental testing of auditory alarms should be considered from human factors point of view as both the standards and literature suggests this to be the most effective design for operators.

## 6. Conclusion

The overall objective of this research is to do a review of alarm design methodologies for the process industry in order to provide inputs to different industry partners. This has been identified in peer-reviewed journal articles and conference papers collected from a SLR.

RQ1: *"What type of design process/methodology have been used for making a set of auditory alarms intended for the process industry?"*

By the design of auditory alarms, the standards have more of a focus on *what to do* rather than *how to do it*. Auditory alarms should be made in accordance with standards and human factors research and methodologies. Ideally, similar to the experimental design in the studies by Sikka et al. (2014) and Fagerlönn et al. (2017), where one makes the alarms in accordance with a specified standard of once choosing, and has the end-user follow along the whole process to provide input. This is needed to understand the underlying principles on how to create alarms intended for the operator, where he/she is the one that will be actively listening to these sounds in the future and should know how to quickly respond upon hearing it. This is made easier for sound designers in the differing standards, where the alarm philosophy will help the designer to understand what the auditory alarms should be based on to be appropriate to the different priorities.

RQ2: *"What type of characteristics should be specified for auditory alarms intended for the process industry?"*

The appropriateness of an alarm in control rooms gives the operators a subjective rating that the alarms are in accordance with the alarm philosophy, and how well it fits in the control room. The auditory alarms in the process industry should have the characteristics of a high perceived urgency and low perceived annoyance. Perceived urgency may affect how quickly the operator will recognize and respond to an alarm and perceived annoyance may influence the operator to ignore the alert. This resolves the challenge of auditory alarms by having a higher perceived urgency being more prioritized by operators and making them less annoying for operators to make them more tolerable. Perceived urgency and annoyance are two characteristics that should be considered when conducting an urgency mapping of the auditory alarms, where this gives a good interoperation of which of the auditory alarms is the most appropriate for the operator in the different priorities' alarms should be in accordance to the standards.

Process industries should have well-established standards to guide alarm designers through the whole process of the alarm management needed for their control rooms operations. Nevertheless, I highly encourage alarm end-users and manufacturers to work closely to improve alarm design for specific alarming devices by being included through the whole process. The possibility for standardization across devices and manufacturers in improving alarm safety should be discussed in future collaboration between alarm manufacturers, end-users (operators) and regulators.

This research has demonstrated general methods that will allow designers, together with the users of the system, to take these findings into consideration when designing in their own auditory alarm methodology.

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# Appendix A

## Evidence Table

**Citation**

**Viraldo, J. and B. Caldwell (2013).**
Study: A introduction in sonification principles in accordance to human factors principles to achieve high level of situational awareness, aiding in sensemaking and decreasing stress.

| Limitations of alarms | Design methodology | Characteristics of auditory alarms |
|---|---|---|
| Alarm flooding | Mentions the use of EEMUA for guidance | Learnability (Easy to learn for operators) |
| Alarm fatigue | Introduces sonification principles | Adjusting (alarm sound): |
| | New to the HF research | Pitch; Tones; Amplitudes; Loudness; Tempo |
| | Presentation of numerical data in the form of auditory signals | |
| | Designed to effectively convey the appropriate meaning to the user | |
| | Solution to reduce alarm flooding and alarm fatigue | |

**Brown, N. (2003).**
Study: To present an overview of the alarms issue and how significant improvements can be achieved within reasonable time and money constraints.

| Limitations of alarms | Design methodology | Characteristics of auditory alarms |
|---|---|---|
| Standing alarms | Using EEMUA Guidelines | Prioritization (Urgency) |
| Nuisance and repeating alarms | | |
| Alarm floods | | |

**Bransby, M. (1999).**
Study: A review of major accidents in regards control room alarm systems

| Limitations of alarms | Design methodology | Characteristics of auditory alarms |
|---|---|---|
| Poor performance of alarm systems | IEC 61508 | Prioritization |
| | EEMUA Guidelines | |
| | Core principles for design: | |
| | 1. Usability | |

| | | |
|---|---|---|
| | 2. Safety | |
| | 3. Performance Monitoring | |
| | 4. Investment in Engineering | |

**Reed, D. and T. Z. Strybel (2004).**
Study: Investigation if perceived urgency of warning sound would affect visual orienting.

| **Limitations of alarms** | **Design methodology** | **Characteristics of auditory alarms** |
|---|---|---|
| Too many alarms in control rooms | In paired-cue conditions, perceived urgency did affect the amount of interference produced by uninformative cues | Urgency mapping of auditory alarms, based of research by Edworthy et al. (1991 |
| | In highly-urgent informative cues, the urgency of the informative cue determined the amount of interference in visual search | |
| | In less-urgent informative cues, the effect of uninformative cue urgency was less clear, because they produced more interference than more urgent uninformative cues. | |
| | Differences in cue interference are caused by an inability to discriminate cues with similar pulse rates. | |

**Xiao, Y. and F. J. Seagull (1999).**

Study: The effectiveness in the use of auditory alarm devices to enhance human monitoring performance in monitoring tasks has been challenging from time to time. Question of what roles alarms should and could assume.

| **Limitations of alarms** | **Design methodology** | **Characteristics of auditory alarms** |
|---|---|---|
| False alarms | The design of alarm devices should be guided by the principle of information provision regardless of whether an alarm may be true or false indication of "alarming" events. | Prioritization |
| Nuisance alarms | Takes inspiration of Stanton (1994) and Rasmussen (1983) framework | |
| Inopportune alarms | Knowledge-, rule- and skill-based behavior of operators hearing an alarm | |
| Operators interested in knowing the underlying changes, but not interested in the alarm mechanism's interpretation of the changes | Focus on information provision, rather that the interpretation of system change | |
| | Suggestion for human operators to be better informed of changes made in alarms, instead of what a change may signify | |

**Fagerlönn, J., et al. (2017).**
Study: Development of a new type of multimodal warning display for a paper mill control room

| **Limitations of alarms** | **Design methodology** | **Characteristics of auditory alarms** |
|---|---|---|
| Inadequate urgency mapping | Auditory icons to be used in the design phase | Effectiveness |
| Tonal warnings are challenging to learn and interpret – increased level of cognitive load. | Combining visual and auditory cues are beneficial | Acceptance |
| Auditory masking and hearing impairment may increase the risk that important information is lost | User-driven process – involving operators of the control room | Urgency mapping – help with prioritization of incoming information |
| | | Auditory Icons – meaningful non-speech sounds |
| | | Sequence of warning sound – one part (tonal component) convey urgency information, second part (auditory icon) convey information about relevant selection. |

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**Johannsen, G. (2004).**
Study: Investigation of several types of auditory displays to be compared for different types of applications.

| **Limitations of alarms** | **Design methodology** | **Characteristics of auditory alarms** |
|---|---|---|
| Overload of alarms | Real human end users have to be investigated by means of task analyses in early design stages. | Urgency |
| Auditory display are often superior to visual display | 1. Application-Oriented Classification | Expressiveness |
| | 2. User-Oriented Classification | Annoyance |

| | | |
|---|---|---|
| | 3. Sound Orientation Classification | |

**Sirkka, A., et al. (2014).**

Study: Investigation on the best practice to convey urgency information in industrial control rooms

| **Limitations of alarms** | **Design methodology** | **Characteristics of auditory alarms** |
|---|---|---|
| Alarm sounds today are too loud, too numerous and too confusing. | In accordance with the EEMUA-191 | Urgency – changing spectral and temporal parameters |
| Not enough auditory displays assist operators effectively | Urgency Mapping | Annoyance – loudness, sharpness duration and tonality |
| | Involve the end-users in the design process | Distinctiveness |
| | Keep perceived urgency high, while perceived annoyance should be kept at a low level in the alarm sounds. | |
| | A sound signal that is both effective and has non-annoying characteristics is more likely to become tolerable. | |