Alarm Management for human performance. Are we getting better?

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Industrial alarm systems are very crucial for the process safety and operational efficiency of modern industrial plants including oil gas, chemical, petrochemical and power plants. With the evolvement of control systems, in particular, Distributed control systems (DCS), the number of alarms in a plant has increased dramatically leading to high operators' workload, poor system performance and in some cases fatal accidents. The EEMUA 191 guideline and the ISA-18.2 standard along with the IEC 62682 and others define the recommended and required practices for effective alarm management. For instance, alarm rationalization is a key stage in the alarm management lifecycle defined in ISA-18.2. It seeks to define the optimal and most effective set of alarms needed to keep the process safe and within normal operating limits. This paper aims to investigate the improvement of alarm management practices during the last 2 decades in the oil gas industry and its current challenges. It also provides a review of different existing regulations, standards and guidelines along with the recommended performance evaluation practices used in the field.

Keywords: Alarm management, human performance, Alarm performance, Alarm improvement, Oil and Gas industry, Alarm flood.

1. Introduction

Alarm management, as defined by the International Society of Automation (ISA), is the collection of processes that ensures an effective alarm system (ISA (2009)). It is also, the application of human factors, instrumentation engineering, and systems thinking to manage the design of an alarm system to increase its usability (Crompton (2021)). Alarm systems form an essential part of the operator interfaces to large modern industrial facilities. They provide vital support to the operators by alerting them to plant processes, conditions, or equipment malfunctions and warning them of situations that need their attention. A good alarm management system can help bring the operating process closer to its optimal operating point, resulting in lower production costs, higher quality, and ultimately safer operations. Poor alarm management, on the other hand, causes downtime, unsafe situations, and can even lead to industrial fatal incidents (Srinivasan et al. (2004)). For instance, the piper alpha accident in 1988 resulted in 167 deaths, the destruction of the offshore platform and financial losses of an estimated £2 billion (Cullen (1993)). The explosion at the Milford Haven Refinery in 1994, caused 26 injuries and an estimated financial loss of £48 million (HSE (1997)). In 2005, The BP Texas refinery explosions and fires killed 15 people, injured another 180 and resulted in financial losses exceeding $1.5 billion (Safety and Board (2007)). The BP Deepwater Horizon blowout in 2010, resulted in 11 fatalities, 16 injuries and a continuous flow of hydrocarbons into the Gulf of Mexico, causing the largest oil spill in U.S. history and significant environmental damage to the Gulf of Mexico (Guard (2010)). In 2018, the Pryor Trust Well Gas Well Blowout and Fire killed 5 workers who were inside the driller's cabin on the rig floor (Safety and Board (2019)). Following investigations, the primary causal factors identified in each of these accidents were related to

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poor alarm management and alarm floods and in some cases, they could have been prevented. (see Table 1).

Table 1. Example of major accidents in which poor alarm management practices was a root cause.

Year	Accidents	Causal factors
1988	piper alpha	False alarms issue
1994	Milford Haven Refinery	Poorly prioritized alarms and alarm flood
2005	BP Texas refinery	Failed alarm management
2010	BP Deepwater Horizon disaster	Bypassing of alarms and shutdown devices
2010	Kalamazoo River oil spill	Operators disregarded both alarms and procedures
2012	Columbia gas transmission corporation pipeline rupture	Controller didn't recognize the alert of leak
2018	Pryor Trust Well Gas	Alarm system off excessive nuisance alarms and lack of critical ones

Source: HSE (1997), Cullen (1993), Safety and Board (2007), Guard (2010), Goel et al. (2017), Board (2010), Board (2014), Safety and Board (2019)

Therefore, Alarms must be configured to notify only the necessary events, preventing excessive information from confusing operators. On this basis, Alarm rationalization entails systematically investigating the existing alarms and defining the attributes of each one (such as limit, priority, classification, and type), as well as documenting the cause and effect, response time, and operator action to reduce alarm load on operators by displaying only true alarms that are relevant and require operator action Ghosh and Sivaprakasam (2020). Furthermore, alarm rationalization, as defined in EEMUA guideline EEMUA (2009).is a process whereby a multi-function team determines what alarm configuration (priority and settings) is required for individual parameters in the control system. This review paper provides insights into the current state of alarm management practices with a focus on the alarm rationalization process within the O&G industry, how they have been improved over 2 decades, existing regulations, standards and guidelines and summarizes the challenges of achieving effective alarm management. The remaining sections of the paper are organized as follows. Section 2 provides an overview of the different norms and technical documents used for alarm management good practices in the oil & gas industry. Section 3 discusses the process of alarm improvement highlighting the importance of alarm rationalization. Section 4 provides a comparison of the key recommended evaluation criteria for alarm performance, explains why there is still an issue with the current practices and discusses a concrete example by providing the results of an exploratory analysis of process alarm data from an oil gas offshore platform in the north sea.

2. Guidelines, standards and best practices of alarm management in the Oil Gas industry

Due to the high-risk and complex nature of the Oil gas industry and offshore sector, significant efforts have been made in the past decades to reduce human error and create a safe workplace. Experiences and lessons learned on human factors have been accumulated around the world and thus translated into standards, guidelines and best practices.

2.1. *Guidelines*

Rothenberg (2009) defines in his book, guidelines as standards or principles that can be used to make a decision or to determine a policy or course of action. The author also advised adopting a consistent approach rather than picking parts from different authors when using guidelines as they may be incompletes. EEMUA 191, Alarm Systems: A Guide to Design, Management, and Procurement, published in 1999 by the Engineering Equipment and Materials Users' Association (EEMUA), based in the United Kingdom is the globally accepted and leading guideline for alarm management's good practices. This guide is neither a standard nor a regulation but contains the backbone of almost every standard and regulation concerning alarm management. Therefore, it is an extremely valuable resource for understanding what is required in appropriate alarm system design and operation.

2.2. *Standards*

Standards are a pre-established set of rules established by an approved entity governing acceptable practices. They are primarily intended to promote safety, dependability, productivity, and efficiency. Design, operation, construction, and other aspects may be included in such practices. The main standards bodies in the field of alarm management are ANSI (American National Standards Institute) in the United States, ISO (the International Standards Organization), IEC (International Electrotechnical Commission), NAMUR (User Association of Automation Technology in Process Industries) in Germany, API (American Petroleum Institute) in the United States, PSA (Petroleum Safety Authority Norway) in Norway. ANSI/ISA 18.2 (ISA (2009)) was first published in 2009 by the International Society of Automation with the support of the American National Standards Institute (ANSI). It was built on the recommendations of EEMUA 191 (EEMUA (2009)) with the intent of bringing those practices up to date. It served as a breeding ground for alarm management standards, filling a global need and a foundation for the European Standard IEC 62682 NSAI (2015).

2.3. *Best practices*

Best practices are processes or techniques that have been shown to consistently produce better results than alternative designs or approaches. They may be from standards, guidelines or long experiences and be established by authorities such as regulators, self-regulatory organizations (SROs), or other governing bodies, or can be established internally by a company's management team. The Health and Safety Executive (HSE) is a formal aspect of the United Kingdom government and has no current specific standards, guidelines, or recommendations that govern alarm management for the general process industries but is keeping the industries aware of the generally accepted best industrial practices by documenting and sharing incidents and lessons learned. Following the investigation of the Milford Haven Refinery explosion, HSE initiated a survey of the performance of alarm systems in the chemical and power industries to determine current best practices in the procurement, design and management of alarm systems. The results were published in the alarm management process report (Bransby and Jenkinson (1998)) and are still considered a good guide for best practices.

2.4. *Technical norms and documents*

Chandrasegaran et al. (2020) presented in their research paper the different human factors engineering (HFE) norms and regulations used in the oil gas industry. These norms and regulations are developed to convey the HF goals and expectations in terms of prescriptive descriptions for safe facilities operation. Table 2 summarizes the norms considered by Chandrasegaran et al. (2020) and includes others in which alarm management is regularized or discussed as part of HFE in the offshore of oil & gas industry.

While there are few regulations for alarm management, there is a lot of consensus among the existing standards and recommendations in which alarm improvement technique is a standard engineering procedure Rothenberg (2009).

In the next section, characteristics of a good alarm system along with alarm improvement techniques are discussed.

3. Strategy for Alarm improvement

3.1. *What's a good alarm system?*

According to EEMUA 191 EEMUA (2009), an alarm system should direct the operator's attention towards plant conditions requiring timely assessment or action. A good one, assists the operator in resolving potentially hazardous situations before the Emergency Shutdown (ESD) system is forced to intervene. It is identified by the following attributes:

Relevant. not spurious or of low operational value

Table 2. Standards and technical norms used within the offshore oil gas industry in which alarm management is regularized or discussed.

Document title	Synopsis	Key Evaluation criteria for AM	Operator's perspective
Standards Organization			
ISO 6385, Ergonomics Principles in the Design of Work Systems	It provides the philosophy for designing the work systems with ergonomics principles; from establishing the goals to evaluation of the designed work systems. It also stipulates involvement of ergonomists during the design development process.	No metrics provided	Not explicitly considered
ISO 11064 - part 5, Ergonomics of human-system interaction.	This part of ISO 11064 presents principles and gives requirements and recommendations for displays, controls, and their interaction, in the design of control-centre hardware and software.	Average number of alarms per control room operator per hour; Number of standing alarms associated with "on-line" equipment (per control room operator); Number of defeated alarms associated with "online" equipment; Number of incidents and significant near misses where the alarm system was a contributing factor.	Not explicitly considered
ANSI/ISA-18.2, Management of Alarm Systems for the Process Industries	It specifies general principles and processes for the lifecycle management of alarm systems based on programmable electronic controller and computer-based human-machine interface (HMI) technology for facilities in the process industries, covering all alarms presented to the operator.	Annunciated Alarms per Time (day, hour and 10 minutes); Percentage of 10-minute periods containing more than 10 alarms; Maximum number of alarms in a 10 minute period; Percentage of time the alarm system is in a flood condition; Percentage contribution of the top 10 most frequent alarms to the overall alarm load; Quantity of chattering and fleeting alarms; Stale Alarms; Annunciated Priority Distribution.	Audit Interviews
IEC 62682, Management of Alarm Systems for the Process Industries	It was written as an extension of ANSI/ISA-18.2, incorporating more requirements and slightly modifying some content for simplicity.	Same as ANSI/ISA-18.2	Not explicitly considered
NAMUR NA 102, Alarm Management	It provides a procedure for designing alarm management within a process control system starting from a global view of the process as a whole.	No metrics provided	Not explicitly considered
API RP 1167, Pipeline SCADA Alarm Management	It provides recommended industry practices in the development, implementation, and maintenance of an alarm management program.	Taken from ANSI/ISA-18.2 standard	Not explicitly considered
PSA YA-711 - Principles for design of alarm systems	It provides basic principles and guidelines on alarm generation, structuring, prioritization, and presentation for offshore installations on the Norwegian Continental Shelf.	Rate of incoming alarms (with priority distribution); Number of alarms in main list (with priority distribution); Operator response times (time before acceptance); Frequency distribution of alarms: For identifying any "bad actors" that contribute significantly to the overall alarm load.	Not explicitly considered
Classification societies			

ABS (American Bureau of Shipping) Guidance Notes on The Implementation of Human Factors Engineering into the design of Offshore Facilities	It provides a strategy for integrating and implementing HFE into the design process as a way to help improve human performance and personnel efficiency and reduce safety risks associated with working and living on offshore installations.	No metrics provided	Not explicitly considered
ABS Guidance Notes on Application of Ergonomics to Marine Systems	It provides the design and layout guidance related to ergonomics at sea, including the design of human-system interfaces at the individual task and workstation levels. Physical and perceptual issues for the design of the personnel interface with controls, displays, alarms, video-display units, labelling, workspace access, and workspace arrangement are discussed in the document.	No metrics provided	Not explicitly considered
Industry groups			
EEMUA 191, Alarm systems: a guide to design, management and procurement	It provides guidance on designing, managing and procuring an effective alarm system. It is intended to help in improving existing systems and in developing new facilities during plant construction or during alarm system refurbishments.	Average alarm rate; Maximum alarm rate; Proportion of time alarm rates are outside of acceptability target.	Usefulness questionnaire; Operator questionnaire
NUREG-0700, Human-System Interface Design Review Guidelines	It provides the guidance for conducting detailed control room design reviews and identifying and correcting design deficiencies in order to bring control rooms into compliance with human factors engineering principles.	No metrics provided	Not explicitly considered
ASM (Abnormal Situation Management) Consortium Guideline : Effective Alarm Management Practices	It provides alarm management best practices designed to reduce alarm floods and ensure that process operators can respond effectively to alarms.	EEMUA performance metrics benchmark by 37 consoles at ASM Members' sites	Not explicitly considered
Government agencies			
The management of alarm systems (by Bransby, M.L. and J. Jenkinson)	It provides review of current practice in the procurement, design and management of alarm systems in the chemical and power industries	Average number of alarms over a defined period of steady operation; Number of alarms following defined plant transients (eg. a planned plant trip); Proportion of alarms occurring at each priority; The percentage of useful alarms.	Opinion survey of operators; Survey of operators of the "usefulness" of alarms; Survey of engineers.

Source: EEMUA (2009); NSAI (2015); ISA (2009); Bransby and Jenkinson (1998); Errington et al. (2009); O'Hara and Fleger (2020); Organization (2008); for Standardization (2004); YA (2001); (API) (2010); of Shipping (2014); c/o Bayer Technology Services GmbH (2013)

Unique. not duplicating another alarm.
Timely. not actuate too early before a response is needed; nor too late for the operator to properly respond.

Prioritized. indicating the importance that the operator manages the situation.
Understandable. having a message that is clear and easily recognized.
Guiding. Drawing attention to the most important issues and indicative of the action to be taken.

3.2. *Alarm performance assessment*

As process conditions change and alarm sensors age over time, it is most likely that an alarm system's performance deteriorates. Thus, it is crucial to have an ongoing alarm performance evaluation that helps maintain operating effectiveness. Alarm performance assessment is the process of determining how well the alarm system is assisting the operator. It is also the comparison of data from monitoring and other qualitative (subjective) measurements to stated goals and defined performance metrics (ISA (2009)). Rothenberg (2009) has identified two core data sources for alarm performance evaluation: Performance data which consists of minute-by-minute recordings of alarm activations, acknowledgements, operator actions... (produced by the system when alarms occur), and configuration data (static alarm database) which contains all alarm attributes that appear in the control system. Both categories are valuable for the assessment of alarm system performance and are susceptible to different evaluations.

3.3. *Alarm Rationalization*

Alarm improvement revolves around rationalization. It's the method or process to reconcile each alarm against the principles of alarm philosophy. It is a critical step in the alarm management lifecycle as defined in the ANSI/ISA standard and a requirement to create an effective alarm management system. It consists of alarm classification, prioritization, rationalization and documentation and results in a collection of proper alarm settings for the system known as a Master Alarm Database. There are two basic approaches of alarm rationalization process Rothenberg (2009):

- Starting from the existing configuration; It consists of reviewing every existing alarm and determines whether to keep it as it is, modify its configuration or eliminate it based on the alarm philosophy document.
- Starting from scratch by initially assuming that the entire plant has no configured alarms.

Both approaches aim to reduce the number of alarms configured and that each one of them is understandable, prioritized, relevant, unique, and timely. To achieve a successful alarm rationalization using the first approach, it is important to identify the alarm system's most pressing issues. A way to do so is to analyze the alarm system and by measuring key performance indicators and comparing them to the established targets in the different guidelines and standards. In the next section, we will discuss alarm performance and the most used evaluation criteria as per standards and guideline.

4. Alarm performance

4.1. *Evaluation criteria for alarm systems*

The performance of alarm systems can be assessed from different perspectives, mainly the system's perspective, the operator's perspective or both Wu et al. (2017). In the different norms and standards documents, the evaluation of alarms was presented from the system's perspective using different metrics and Key performance indicators (KPIs) and very few of them take the operator's behaviour into consideration. Table 2 gives insights about the different documents regularizing the alarm management and if they include alarm performance criteria and if the operator's perspective is taken into consideration.

4.2. *Performance metrics, KPIs and benchmark*

Key performance indicators (KPIs) determine the performance level of an alarm system by measuring its features and comparing them to predetermined targets as defined in the EEMUA guideline, the ANSI/ISA 18.2 standard and other norms. These KPIs are defined over a period. For computing these metrics, at least 30 days of data is recommended ISA (2009). Table 3 presents key evaluation criteria for alarm system performance as defined in the guidelines and standards.

Table 3. This is the caption for this Table in font 9pt. Short line caption must be centered.

Evaluation criteria	Guideline documents	Recommended metric value
Criteria 1: average alarm rate		
Long term average alarm rate in steady state operation	EEMUAA 191	$\leq$ 1 per 10 minutes
Average alarm rates	IEC 62682	$\leq$ 2 per 10 minutes
Average alarm per control room per operator per hour	ISO 11064-5	$\leq$ 1 per 6 minutes
Average Annunciated Alarm Rate per Operating Position	ISA-18.2	$<$ 2 per 10 minutes
Alarm rates in steady operational conditions	PSA YA-711	One per 5 minutes
Criteria 2: Peak alarm rate		
Alarms in 10 minutes after plant upset	EEMUAA 191	$<$ 10 per 10 minutes
Maximum peak rate of alarms during upset conditions (per control room operator)	ISO 11064-5	3 to 5 per minute and $<$ 6 in 10 min
Peak Annunciated Alarm Rates per Operating Position	ISA-18.2	$\leq$ 10 per 10 minutes
Criteria 3: Proportion of time alarm rates are outside of acceptability target		
% of time outside average alarm rate	EEMUAA 191	10%
Criteria 4: Average standing alarms		
Average number of standing alarms	EEMUAA 191	$<$ 10
Stale Alarms	ISA-18.2	$<$ 5 per day
Number of standing alarms associated with “on-line” equipment	ISO 11064-5	$<$ 5
Criteria 5: Priority Distribution (low/med/high)		
Priority distribution	EEMUAA 191	80%, 15%,5%
Annunciated Priority Distribution	ISA-18.2	80%, 15%, 5%

Source: ISA (2009), NSAI (2015), EEMUA (2009),

The metrics have different nominations in the distinct documents with approximately the same proposed target values. Many benchmark studies were conducted by different authors and authorities in the field to determine whether the target values of these metrics as set in the guideline and standards are achievable in practice. The ASM consortium conducted an alarm performance metrics benchmark project to determine if the EEMUA recommendations are achievable and what factors influence alarm performance. The evaluation was realised by surveying 37 consoles at ASM members' sites and using 90 months of data. The results of this study showed that the EEMUA recommendation for less than one alarm per 10 minutes period for the average alarm rate in steady operation is achievable. However, the Peak alarm rates are still higher than recommended by the guideline (C.Reising and Montgomery (C.Reising and Montgomery)).

In another research work, C.Reising et al. (2004) conducted a comparative study using two approaches analytical Keystroke-Level Modelling and a Markov modeling to check whether the alarm rate and peak rate recommended values in EEMUA guideline are within human performance limitations for refining and petrochemicals plant's operator or not. The findings suggest that refineries and petrochemical plants should attempt to meet EEMUA recommendations for both average and peak alarm rates.

4.3. *Concrete example: Exploratory analysis of process alarm data*

An exploratory data analysis was conducted on process alarm data collected from an oil & gas offshore platform. The data was collected over 2 months. It consists of summarizing the main characteristics of the alarm data. The analysis allows us to perform an initial investigation of the data, diagnose the current situation of alarms and compare them with the recommended best practices in guidelines and standards.

The plot in Figure 1 shows the count of alarms per day. We can notice that the minimum number of alarms per day exceeds 15 thousand alarms, which is higher than the maximum manageable given in the standards and guideline: an average of 300 alarms per day according to AINSI/ISA 18.2 standard and 288 alarms per day following the IEC 62682 standard (NSAI (2015)).

Figure 2 represents the count of alarms per 10 minutes an operator had to deal with within these 2 months. Again, the values are far from recommended best practices in the different standards and guidelines.

By grouping the count of alarms per 10 minutes by priority, we got the graph in Figure 3. There are four priority levels in the data set: 100, 200, 300 and 500 with 500 being the highest level.

We can notice that the high priority 500 has the highest number of alarms every 10 minutes during the whole period of 2 months. This can only suggest that reclassification of alarms is necessary along with the reassessment of the alarm management system to detect and remove unnecessary/ nuisance alarms that can be the cause behind the high number of alarms.

4.4. *Discussion*

The results of the exploratory analysis combined with the benchmark studies found in the literature show that alarm flood is a very serious problem in the process industry and in oil & gas plants specifically and can't be avoided despite the effort to improve the best and recommended practices. An alarm flood, as defined in EEMUA 191, is the situation where more alarms are received than a human operator can handle, lowering his ability to detect faults and constraining him from taking the necessary course of action. A consequence of this is poor human performance and human error. This may be because most of these practices still don't take into account human behaviour and don't include a strategy on how to improve human performance in alarm management using either objective or subjective methods.

5. Conclusion perspective work

Since the emergence of distributed control systems, various benchmark studies have been conducted on alarm evaluation criteria to validate the effectiveness of the current alarm management practices. However, only a few of them consider the perspective of the operators when evaluating the alarm system. Further, there is no unified standard for operator performance indicators when using an alarm system, and only few of the current standards discuss or mention the human performance for alarm management. Different human performance indicators were suggested in existing research and can be classified into three classes: task performance indicators, cognitive performance indicators, and subjective evaluation indicators. The most commonly used are mental workload, cognitive demand, and situation awareness using objective methods such as physiological records (e.g., heartbeat, winking) (Wu and Li (2018)).

Eye-tracking which involves recording the gaze of a person and provides information on the trace of the attention allocation (Sharma et al. (2016); Bhavsar et al. (2016); Bhavsar et al. (2017)), electroencephalography (Iqbal et al. (2019); Iqbal et al. (2020)), and galvanic skin resistance have all been used to investigate the behaviour of control room operators dealing with process control and results demonstrated to be accurate in inferring various aspects of human cognition. Moreover, mathematical/ computational models such as the Hidden Markov model were developed and used to represent the mental model of control room operators handling an abnormal situation. The approach showed promising results in identifying

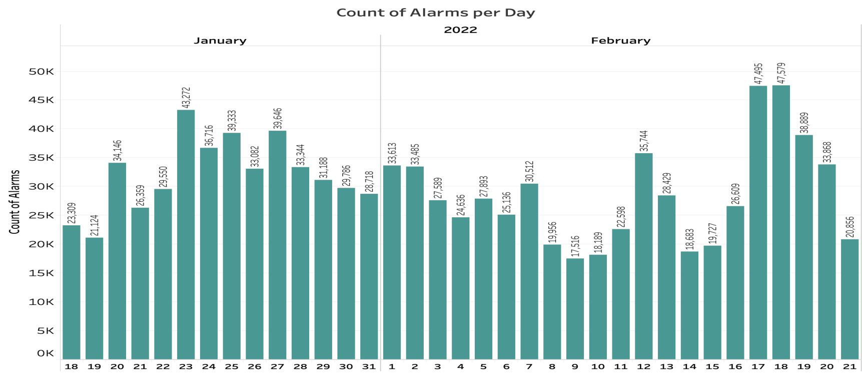

Fig. 1. Count of alarms per day for a period of 2 months

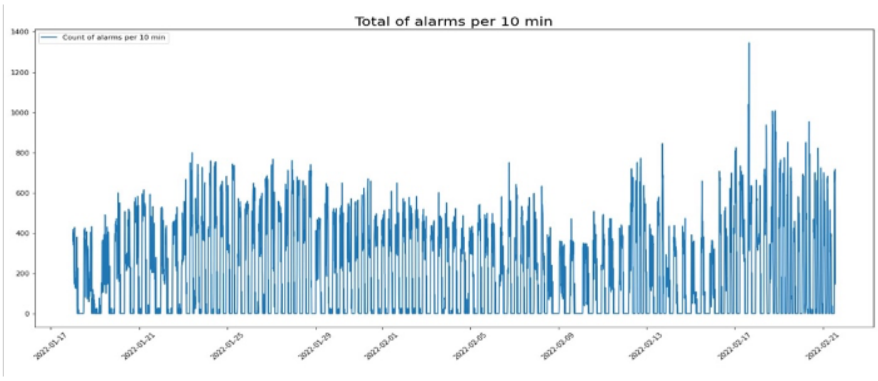

Fig. 2. Total of alarms over a 10 minutes window over a 2 months period

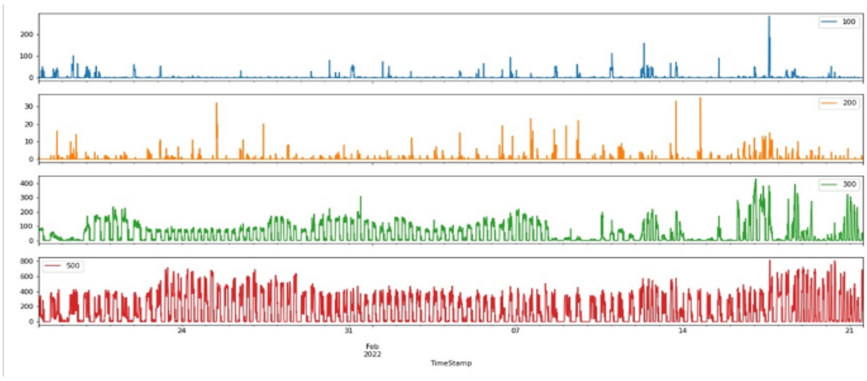

Fig. 3. Count of alarms over a 10 minutes window grouped by priority

the different features in the mental models of operators and the precursors to failure in alarm management (Shahab et al. (2022)).

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