Aiding Alarm Rationalization by Automatic Identification of various sequential patterns in large volume of Alarm and Event log data

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Abstract. The main problem with modern Industrial Alarm System is that the operators receive far too many alarms than they can handle. Many of the alarms presented to the operators are nuisance in nature such as chattering alarms, redundant alarms, consequential alarms, and alarms with no action. Such alarms superfluously increase the alarm load to an operator, do not essentially indicate any real abnormal situation and more importantly do not require any corrective actions by the operator. Being overwhelmed by large number of nuisance alarms, operators always face tough challenge in identifying the real alarms which demands prompt operator actions and are often buried in the pool of nuisance alarms. It is therefore necessary to reduce the alarms loads of an operator by systematically identifying the nuisance alarms and presenting only the real useful alarms to the operators. Also, there are some alarms which require well defined operator actions to bring them back to normal. When these alarms get triggered operators are supposed to take a well-defined set of corrective action in order to normalize them. Identification of these alarms for which there is a consistent operator action would be of immense help since operators can immediately focus their attention on these alarms whenever they occur and carryout the necessary actions. The main goal of Alarm rationalization is to minimize alarm load to the operators by presenting only the alarms that are relevant and require operator actions. Alarm Rationalization process by and large is carried out manually. It is quite tedious, time consuming and requires a lot of manual efforts. To solve the these challenges and to aid in Alarm Rationalization process, a novel approach has been proposed in this paper for identifying the nuisance alarms by analyzing the large volume of Alarm and Event log data. Several Alarm Rationalization activities (such as: Changing Alarm Configuration settings, Alarm Suppression, Alarm grouping, Alarm removal, Alarm Prediction, Standardization of Alarm response Procedure) can be performed by based on the identified chattering alarms. The proposed approach is illustrated through some examples obtained by analysing the Alarm and Event log data from petrochemical and water treatment plants in Singapore.

1. Introduction
As per the industrial standard ANSI/ISA-18.2 [1, p. 16], “an alarm system is the collection of hardware and software that detects an alarm state, communicates the indication of that state to operators, and records changes in the alarm state.” Alarm systems are the integral parts of modern computerized process automation systems such as the Distributed Control Systems (DCS) and Supervisory Control and Data Acquisition (SCADA) systems. Alarm systems play a crucial role for safe and efficient
operations of modern industrial plants such as petroleum refineries, chemical, petrochemical, power, and water treatment plants [2], [3]. The main purpose of the Alarm systems is to promptly indicate the occurrences of any abnormal condition, so that operators can take remedial actions to bring the process back to its normal operating regions. It is a well-known fact that the deviation of process variables from their normal/optimal operating regions usually has a negative impact on the process in terms of off-specification products as well as excessive consumption of raw materials and energy. Although the alarm systems are extremely important for the safety and efficiency of the industrial plant, however, most of the existing industrial alarm systems suffer from the fact that they generate far too many alarms that operators can effectively handle. In Wang et al. [4] this phenomenon is referred to as “Alarm Overloading”. The phenomenon of Alarm Overloading is clearly evident from Table 1 [3], which shows statistics of 3 Key Performance Indices (KPIs) of alarms systems, based on a study of 39 industrial plants ranging from oil and gas, petrochemical, power and other industries. The corresponding benchmark values according to the EEMUA-191 guideline [5] are also presented in Table 1 for comparison. Obviously, the statistics of KPIs from various industries are far away from the EEMUA benchmarks.

Table 1: Comparison of Alarm System KPIs across various industries with EEMUA benchmark

| KPIs                  | EEMUA | Oil-Gas | Petrochem | Power |
|-----------------------|-------|---------|-----------|-------|
| Average Alarms/day    | 144   | 1200    | 1500      | 2000  |
| Peak alarms/10 min    | 10    | 220     | 180       | 350   |
| Average alarms/10 min | 1     | 6       | 9         | 8     |

The alarms generated by alarm system can be broadly classified into two groups – (i) nuisance alarms, and (ii) true (real) alarms. A nuisance alarm does not affect the process and hence does not require any specific response or action from operators. According to the industrial standard ANSI/ISA-18.2 [1, p. 18] an alarm must indicate an equipment malfunction, process deviation or abnormal condition requiring a response. A real alarm on the other hand, must indicate an abnormal situation that requires operator to pay attention or take action in a timely manner; otherwise the abnormal situation associated with the real alarm would have an adverse effect on the process safety and/ or efficiency. The nuisance alarms are the major contributor for the phenomenon of alarm overloading [4]. The consequences of alarm overloading are extremely detrimental to the important role played by alarm systems. A large number of alarm generated by the alarm systems are nuisance in nature. They do not provide any useful information and only cause distractions to plant operators. The real (true) alarms are often buried within large number of such nuisance alarms and are often overlooked by operators. As a result, they may work on less important alarms, or attempt to struggle with all alarms or give up on the alarm system completely. Again, there are some true alarms which require certain operator actions to bring them back to normal state. When these alarms occurred operators are supposed to take certain set of corrective actions promptly in order to normalize them. Identification of such alarms for which there is a consistent operator action would be of immense help since operators can immediately focus their attention on these alarms whenever they get triggered and carryout the necessary remedial actions. The identified steps of corrective actions can also be used to standardize alarm response procedure.

Alarm rationalization is a process where a cross-functional team of plant stakeholders reviews, justifies, and documents that each alarm meets the criteria for being an alarm (i.e., the alarm must be relevant and useful, must indicate an abnormal situation and must have necessary corrective actions by the operators) [6]. The principal objective of Alarm rationalization is to minimize alarm load to the operators by presenting only the true alarms that are relevant and require operator actions. Alarm Rationalization also involves defining the attributes of each alarm (such as limit, priority, classification, and type) as well as documenting the cause & consequence, response time, and operator action. Alarm Rationalization process by and large is carried out manually. It is quite tedious, time consuming and requires a lot of manual efforts. Since there are thousands of alarms configured in an alarm system, sometimes it is even difficult to identify a good candidate alarm to be reviewed/examined during the alarm rationalization.

To address some of the challenges discussed above and to aid in Alarm Rationalization process, we propose a novel approach in this paper. The proposed methodology can analyze a large volume of historical Alarm and Event log data in a plant in a systematic manner to identify many useful and
interesting patterns hidden in the data and turn them into actionable information. From the extracted Alarm & Event pattern sequences it is possible to identify various nuisance as well as true alarms that can be potential good candidate alarms for Alarm rationalization. Several Alarm Rationalization activities (such as: modification of alarm configuration settings, Alarm Suppression, Alarm grouping, Alarm removal, Alarm Prediction, Standardization of Alarm response Procedure) can be performed by utilizing this uncovered Alarm & Event relationships. The remainder of this paper is organized as follows: in section 2 we introduce some of the nuisance alarms that are the major culprits for causing alarm overloading. The proposed methodology for aiding alarm rationalization process by identifying some of the nuisance alarms automatically through a systematic analysis of large volume of historical alarm and even log data is presented in Section 3 along with some illustrative examples from real industrial datasets. Finally, the paper is concluded in Section 4 with a brief discussion and direction of future work.

2. Nuisance Alarms

In this section we introduce some of the nuisance alarms that are the major contributors for causing alarm overloading in industrial alarm systems. These nuisance alarms can be good candidate alarms to be reviewed during alarm rationalization process. Several Alarm Rationalization activities (such as: modification of alarm configuration settings, Alarm Suppression, Alarm grouping, Alarm removal) can be undertaken to get rid of these nuisance alarms.

Chattering alarms are the most widely encountered nuisance alarms and may contribute to about 10%–60% of alarm count [3, p. 123]. As per the industrial standard ANSI/ISA-18.2 the chattering alarm can be defined as one that repeatedly transitions between the alarm state and the normal state within a short period of time [1, p.16]. As a result, there is no time for operators to analyze such alarms and take actions. Two closely related nuisance alarms are the fleeting and repeating alarms. Fleeting alarms also have short-time alarm duration, but do not immediately repeat. Repeating alarm on the other hand repeat almost immediately after its recovery, but do not necessarily have short-time alarm duration [1, p. 74]. Chattering alarms are usually triggered due to random noise and/or disturbances on process variables configured with alarms, especially when the process variables are operating close to their alarm limits [5, p. 95].

Redundant alarms and Consequential alarms are next two important nuisance alarms that are often encountered. Redundant Alarms can be defined as a group of alarms that often occur together within a short period of time, typically within a few minutes. Since all the alarms in a redundant alarm group occur within very short period of time it is not possible for an operator to respond to each and every alarm in the redundant alarm group. Furthermore, all the alarms in a redundant alarm group are triggered by the same root cause. Hence, all of them essentially indicate the same underlying problem and do not necessarily require different corrective actions by operators. The incorrectly configured alarm variables are the main reason for the redundant alarms. Many variables are configured with alarms without a careful study on the necessity of configuring alarms on them. As a result, there are a large number of variables that should not be configured with alarms are actually configured with alarms in an incorrect manner. For instance, some industrial facilities were with more than 15000 configured alarm variables, and over 50% of the configured alarm variables had been removed after alarm rationalization [7].

The consequential alarms on the other hand, are the group of alarms that occur one after another in a sequential manner with a significant time difference (typically 5 minutes of more) between the alarms. Since the time difference between the alarms in a consequential alarm group is more than 5 min, therefore, it is possible for the operators to take the necessary remedial actions in a timely manner upon occurrence of the precursor alarm(s) to prevent the subsequent alarms in the consequential alarm sequence. The consequential alarms occur due to propagation of abnormality owing to physical connections. A large-scale industrial process is usually composed of upstream and downstream devices, which are physically connected. An abnormal condition in one process unit is very likely to be propagated to the downstream devices or the upstream devices owing to automatic control loops or recycling connections. As a result, as the abnormality propagates, a sequence of alarms may arise over a period of time from the process variables associated with these devices configured with alarms.

As discussed in Section 1, that every true alarm must indicate an abnormal condition and must need corrective actions by operators in a timely manner, otherwise the abnormality associated with the true alarm would have an adverse impact on the process. A brief definition of alarms given by Rothenberg
as “Alarm Activation = Operator Actions”. Therefore, the alarms which do not require any relevant operator action to bring them back to normal state can also be considered as nuisance. Such nuisance alarm i.e., alarms with no relevant operator actions do not affect the process and do not indicate any abnormal situation. Again, on the contrary, there are some true alarms which require a well-defined operator actions to bring them back to the normal state. When these alarms occurred operators are supposed to take certain set of corrective actions in a timely manner order to normalize them. Identification of such alarms for which there is a consistent operator action would be of immense importance since operators can immediately focus their attention on these alarms whenever they get triggered and carryout the necessary remedial actions. The identified steps of corrective actions can also be used to standardize alarm response procedure.

Next, we present the proposed methodology to systematically identify the nuisance alarms discussed above. The identified nuisance alarms can be potential good candidates for alarm rationalization.

3. Methodology

The flow chart of the proposed methodology is presented in Figure 1. At first, chattering alarms are identified and removed from the historical Alarm & Event log data. An efficient algorithm is used for identification of chattering alarms and their subsequent removal from Alarm & Event log data. After identification the chattering alarms the alarm rationalization activities that can be carried out to get rid of them include alarm configuration changes such as modifications in alarm hysteresis, ON-OFF delay timer settings [8, 9]. If the chattering alarm is due to excessive noise in process variable configured with alarm then appropriate filter can be applied to remove the noise and to smoothen the signal [10]. Again, if the chattering alarm is caused by the oscillation then the root cause of oscillation (e.g., improper PID controller tuning) has to be identified first and subsequently the appropriate corrective actions (e.g., re-tuning of PID controller) should be taken to remove the root cause of the oscillation [11].

We applied this efficient chattering alarm identification and removal algorithm on a historical Alarm & Event data from a water treatment plant in Singapore which suffers from very high alarm count with average of about 2000 alarm occurrences per day. The algorithm was able to identify all the chattering, fleeting and repeating alarms in the data. It was found that the identified chattering alarms (including fleeting and repeating alarms) contributes to about 80% of total alarm count. After removing all the identified chattering alarms the alarm count was reduced to about 400 alarm per day.

After removing the chattering alarms, the de-chattered Alarm and Event log data was used to identify the useful and interesting patterns hidden in the data. It should be noted here that the chattering alarms are considered as noise in Alarm & Event log data and hence they should be removed first before applying any data pattern mining algorithm to identify the patterns in the data. Otherwise, the identified
alarm and event pattern may contain a lot of spurious patterns. We have used an efficient sequential pattern mining algorithm, developed in house at Yokogawa, Singapore for identifying the useful and interesting patterns in the alarm and event log data. The details of the algorithm is not discussed in this paper due to its confidentiality. Various nuisance alarms that can be identified from the extracted alarm & event patterns are discussed below.

Identifying the alarms with no relevant operator actions

From the Identified Alarm and Event pattern if it is found that that for an alarm consistently there is no related operator action in between its every occurrence and recovery, then probably, this alarm is not very important one since it does not need any operator intervention to bring it back to normal and could be a good candidate for alarm suppression or logging or removal (See Figure 2 below). Thus identification of these alarms and subsequently their suppression would result in significant reduction in alarm count.

![Figure 2: Alarms with no action (Potential candidate for Alarm Suppression)](image)

When applied to de-chattered Alarm and Event log from a water treatment plant in Singapore the proposed algorithm was able to systematically identify the nuisance alarms that do not have any relevant operator actions. It was found that the top 20 no-action nuisance alarms contribute to about 7% of total alarm count.

Identifying alarms with consistent operator actions

From the Identified Alarm and Event pattern sequences if it is found that for an alarm there is a certain set of related operator action that are performed consistently in between its every occurrence and recovery, then that alarm will be identified as the alarms with consistent operator actions. Probably, these alarms are important ones since they have to be handled in a certain specific manner in order to bring them back to the normal state. Therefore, identifying such alarms and the sequence of necessary operator actions that follows the alarms can be captured in a knowledge repository to help the operators in easily handling them (See Figure 3 below). The sequence of operator actions required to handle such alarms can be standardize and documented during the Alarm Rationalization Process.

![Figure 3: Alarms with relevant operator actions (Potential candidate for Standardizing Alarm Response Procedure)](image)

An example of alarm with consistent operator action is presented next (See Figure 4 below). This example is obtained by analyzing historical alarm and event log data from a petrochemical plant in Singapore. Sequence of operator actions between a Flow High Alarm activation and recovery are presented below.
Figure 4: Sequence of operator actions between a Flow High Alarm activation and recovery

Here, a High alarm in a flow variable is first handled by manipulating/adjusting/fine tuning the manipulated variable (MV) of the flow loop in manual (MAN) mode. After which the flow loop is taken in auto (AUT) mode and the set point (SV) of the flow variable is adjusted further.

Identification of Alarm Grouping/clustering

From the identified Alarm and Event Pattern sequences it is possible to obtain a group or cluster of alarms in a sequence. Such alarm patterns can be classified into two categories based on the time difference between the alarms in the sequence – (i) Redundant Alarms: The alarms in an identified pattern that occur within a very short interval of time (typically within less than 5 min) from each other and (ii) Consequential Alarms: The alarms in an identified pattern that occur with a significant interval of time (typically more than 5 min) from each other. Steps involved in identifying the redundant and consequential alarms are depicted in Figure 5 below.
Further, following actionable insights can be inferred from the identified alarm groups/cluster.

- **Suppression of redundant alarms**
  
  Redundant Alarms are possibly triggered by the same underlying root cause. Redundant alarms can be suppressed, since they do not provide any additional information. This will reduce Alarm rate significantly.

- **Grouping of redundant alarms**

  The redundant alarms are most likely to be triggered by the same underlying cause and all of them possibly indicate the same problem and hence, have the same corrective actions as well. So all the alarms in a redundant alarm group are not important and may be just one of them would be enough to indicate the actual underlying problem. Thus all the alarms except one representative alarm can be suppressed or removed, since they don’t provide any additional information. This will reduce Alarm rate significantly. Redundant alarms can be grouped together into a single alarm group. Thus, reducing the alarm load significantly.

Figure 6 presents an example of redundant alarm group which is obtained after analyzing the alarm and event log from a petrochemical plant in Singapore.

Here, 3 alarms - Pump P1 motor stop, vessel V2/3 pressure low and pump P1 run alarms always occur together within a very short period of time (~22 sec) and all these 3 alarms are triggered by the same root cause.

- **Early Prediction of consequential alarms**
Consequential alarms (Sequence of alarms with significant time differences between two consecutive alarms) can be predicted upon activation of their precursor alarms. Hence, operator can initiate early action to mitigate any detrimental consequence. Example of an identified Consequential Alarms group obtained after analyzing the historical alarm and event log data from petrochemical plant in Singapore is shown below in Figure 7. It can be seen in Figure 7 that the alarm Vessel 1 Pressure Low Low alarm can be predicted ~52 min in advance based on the occurrence of its precursor alarm Vessel 1 level Low.

Figure 7: Sequence of Consequential Alarms with significant time difference between two alarms (Potential candidate for alarm prediction)

4. Discussion

By and large, alarm rationalization is a manual activity. Sometimes it is not easy to identify the good candidate alarms to be reviewed in alarm rationalization process. It is quite tedious, time consuming and requires a lot of manual effort. In this paper, we propose a systematic methodology to identify some of the widely encountered nuisance alarms that cause alarm overload such as chattering alarms, redundant alarms, consequential alarms and alarms with no operator actions. These nuisance alarms can be good candidate alarms for alarm rationalization. Therefore, the manual effort required for finding a suitable nuisance alarm to be considered during the alarm rationalization process can be greatly reduced. Several alarm rationalization activities such as changing Alarm Configuration settings, Alarm Suppression, Alarm grouping, Alarm removal, Alarm Prediction, Standardization of Alarm response Procedure can be carried out based on the identified nuisance alarms. This will lead to significant reduction in total alarm load. The proposed methodology uses an efficient algorithm for identification and removal of chattering alarms. An in-house developed efficient sequential pattern mining algorithm was used for identifying the useful and interesting patterns in the Alarm and event log data. Various nuisance alarms can be identified from the extracted alarm and event patterns. The efficacy of proposed methodology was illustrated through some examples using real industrial alarm and event log datasets from water treatment and petrochemical plants. The advantages of proposed alarm and event mining technique over the conventional association rule mining [12] and correlation analysis [13] based alarm analysis methods are: (i) the proposed method is computationally inexpensive (faster execution time), scalable and can be deployed in a big data framework and (ii) it can also extract the alarm and event pattern sequence of longer duration (few hours or more) and provide the sequence information as well as time difference between two consecutive alarms in the sequence, which conventional methods cannot. We intend to extend the proposed approach for predicting the impending the alarm flood situations in plant well in advance.

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