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DRAFT

Evaluation of Parallel Coordinates for Interactive Alarm Filtering

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Abstract Alarm management is a crucial part of many industrial systems used in generation, transmission and distribution of electric power as well as in production processes, for example in steel mills and oil refineries. Filtering of important alarms from unessential alarms is a critical task for operators of such systems, since failures may result in severe abnormal situations such as plant shutdowns. Currently, alarm filtering tasks are performed with alarm lists that offer limited interactivity. We evaluated an application of Parallel Coordinates for interactive filtering of alarm data by comparing its user performance against typical alarm lists. Statistical results demonstrate marginally significant evidence ($p<0.1$) for easy and moderate tasks while there is a highly significant evidence ($p<0.01$) for difficult tasks that Parallel Coordinates reduce alarm filtering time. Furthermore, Parallel Coordinates were found to reduce human mistakes.

Keywords Evaluation; Parallel Coordinates; Alarm Management

I. INTRODUCTION

Industrial processes or automation systems for utilities like electricity, gas, and heating or production plants for paper, steel and chemicals run into numerous abnormal situations every day. These abnormal situations have to be rectified for reliable and non-disruptive operation of utilities and production processes. An abnormal situation in such industrial applications is reported as ”Alarms” which are information about the upset or abnormal conditions in the process. Alarms contain information such as the place the alarm occurred - a device or section of the plant - the description of the alarm - the actual problem - and other parameters like priority, category and time of occurrence.

Alarm management is the core of such industrial applications. Good alarm management is the key to ensuring safe and normal operations. Over time, processes and requirements in the industry change, this can result in alarms that have never been seen before. This reinforces the need for proper alarm management in such processes. [1]

Alarm management has many aspects, among which visualization of alarms holds much importance. Traditionally, alarms have been represented as lists typically referred to as Alarm Lists. This is mainly because legacy systems from the beginning of the digital era have always contained such representation of alarms. Though these lists serve as a good consolidated view of the alarms, they do not have a sense of trend or correlation in the alarms' data.

There are a high volume of alarms in today's industrial processes which have to be analyzed in order to identify patterns in these processes and especially anomalies in them. Alarms must be visualized in a manner which indicates problems by means of pointing out temporal as well as other non-temporal parameters of these alarms. Interesting patterns can be identified if the different parameters can be compared together to find correlations in the alarm data. A visualization technique which supports this kind of visual analysis of data are the Parallel Coordinates [2], [3].

This study focuses on the use of Parallel Coordinates for alarm management. The objective was to find results which either reject or support the use of interactive Parallel Coordinates as an effective, efficient and intuitive visualization method for analysis of alarm data. Two visualizations namely, Alarm List and Parallel Coordinates were evaluated to see if use of one method is advantageous over the other.

A. Alarm Management in Industrial Processes

Industrial processes for manufacturing, electricity generation and distribution, production, mining, refining and other processes dealing with real-time data acquisition and control, usually have a means of alarm management. Alarm management solutions can be as simple as lists or more advanced solutions that allow filtering and visualization of alarms in different ways for pattern identification for example Parallel Coordinates. The EEMUA guidelines on design, management and procurement of alarm systems define the sophistication of an alarm management system based on different factors among which the number of alarms is one factor [4]. Depending upon the application domain and its scope, the number of alarms in an alarm management system can range from a couple of hundreds to thousands at a time.

Applications like the one presented in Figure 1 have one main purpose, to present all the important parameters upfront and keep the operator informed about the processes' abnormal states i.e., alarms. This is a challenging task because of the large number of events occurring in such processes. These events could range from malfunctioning equipment to level of a tank's contents to temperature in a furnace. Industries need to be able to visualize and filter important alarms from the rest of the alarms for purpose of complying with process requirements on production, safety and quality. [5]

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Figure 1. Alarm management in a process control application. The area on top of the screens in front of the operator show red blocks indicating alarms and part of the alarm list.

B. Interactive Filtering and Visual Pattern Identification of Alarms

When analyzing alarms from an industrial process, not only is the volume of alarms very large, but there are several parameters within these alarms that need to be monitored. Data about the states of different parts of the process comes in every few seconds and it needs to be observed and acted upon to ensure error-free operation.

The operators should be able to pinpoint trouble areas and important events that occur while the process is running. Equipping the operators to filter out unwanted data helps in focusing on the more important and critical data related to alarms. Additionally, enabling the operators to visually identify patterns that show trends in the alarm data and analyze relationships inferred from these trends, critical information about the process can be revealed. This information can then facilitate maintenance and troubleshooting in industrial processes.

A visual pattern represents a typical behavior which shows the progress of certain process parameters over time. For instance, a certain alarm occurring at a particular time of day or at repeated intervals. However, a rather different and interesting pattern could be the relation between two parameters and how they affect each other and the overall process. For example, a

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particular type of alarm is always followed by another known alarm or, manual operation results in more high priority alarms. Among the two types of patterns mentioned, the latter is comparatively difficult to identify. Such patterns are usually not visible in lists unless the data is visualized in a way other than lists which supports identification of patterns. Visualizing such relationships could lead to better awareness about the processes' state and facilitate better decision making.

C. Alarm Lists vs. Parallel Coordinates

The Alarm List in Figure 2 shows the existing and typical way of representing alarms in the system. This list is typically very long depending upon the time of day, week, month or year and the nature of operations being carried out. While the number of alarms on a display can be reduced to some extent by means of shelving, suppressing and state-based alarming (see [1], [4]), the alarm lists are inherently incapable of visualizing patterns and relationships in the data. A study on comparison of tabular and graphical displays [6] indicates that lists or tabular visualization of data are not suitable of tasks like trend analysis, interpolation and forecasting as compared to graphical visualizations. However, the study also indicated that lists are better at identifying specific values than doing trend analysis as compared to graphical displays. The reason alarms lists have been in use for so long is because they have traditionally been best practices for displaying alarms. However, with the increased number of alarms in the current industrial applications due to changing requirements, better methods of visualizing and managing alarms are needed.

Category	Date	Time	Priority	Type	Message	Acknowledge
Power	2/24/2011	12:53 PM	1	MeasuredValue	Power Line load above 95% - restoring state	False
Controller	2/24/2011	12:53 PM	6	SpontaneousBreakerTrip	I/O unit failure - unable to recover	False
Power	2/24/2011	12:53 PM	6	MeasuredValue	Authorization failure code #536 - restoring state	False
General	2/24/2011	12:53 PM	1	SpontaneousBreakerTrip	Power Line load above 95% - error limit reached	False
General	2/24/2011	11:32 AM	2	MeasuredValue	Authorization failure code #653 - error limit reached	False
Controller	2/24/2011	8:35 AM	3	MeasuredValue	Breaker open failure - error limit reached	False
General	2/24/2011	8:10 AM	3	MeasuredValue	Threshold value 81 reached - unable to recover	False
Station	2/24/2011	7:14 AM	6	HighPriorityAlarms	Threshold value 10 reached - unable to recover	False
I/O	2/24/2011	5:39 AM	6	MeasuredValue	Breaker open failure - restoring state	False
Controller	2/24/2011	5:18 AM	3	HighPriorityAlarms	Breaker open failure - restoring state	False
Controller	2/24/2011	5:01 AM	5	HighPriorityAlarms	Power Line load above 96% - restoring state	False
General	2/24/2011	4:38 AM	6	HighPriorityAlarms	Breaker open failure - unable to recover	False
General	2/24/2011	4:24 AM	6	HighPriorityAlarms	Breaker open failure - alarm severity elevated	False
General	2/24/2011	3:57 AM	2	HighPriorityAlarms	Threshold value 34 reached - restoring state	False
Power	2/24/2011	3:33 AM	4	HighPriorityAlarms	I/O unit failure - error limit reached	False
Station	2/24/2011	3:30 AM	2	HighPriorityAlarms	Breaker open failure - restoring state	False
Controller	2/24/2011	3:25 AM	5	Protection	Threshold value 63 reached - unable to recover	False
General	2/24/2011	2:24 AM	5	HighPriorityAlarms	Authorization failure code #885 - unable to recover	False
Controller	2/24/2011	2:14 AM	4	Indications	Authorization failure code #983 - error limit reached	False
Station	2/24/2011	1:26 AM	4	MeasuredValue	Breaker open failure - alarm severity elevated	False
General	2/23/2011	9:41 PM	4	HighPriorityAlarms	I/O unit failure - error limit reached	False
Power	2/23/2011	9:27 PM	5	HighPriorityAlarms	Breaker open failure - unable to recover	False

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Figure 2. A typical alarm list. A row in the list represents an alarm and each column corresponds to one or more attributes of the alarm.

Knowing the weaknesses and strengths of lists in terms of visual trend analysis, interpolation, forecasting

and identification of specific values, the use of Parallel Coordinates together with lists was suggested as a means of filtering alarm data and identifying patterns visually [7]. As the concept is proposed earlier, this study sought to answer the following research question:

Do Parallel Coordinates improve filtering of alarms in terms of visual pattern identification and trend analysis?

A prototype application has been developed which includes a Parallel Coordinates plot as well as an Alarm List. Filtering and selection techniques were implemented in both the visualizations. There are seven different parameters in the Parallel Coordinates visualization that could be filtered with the help of slider controls in the user interface. The lines passing through the axes in Figure 3 represent the same alarms as in Figure 2. Moving the sliders up and down on the axes filters the alarms which is reflected in both the Parallel Coordinates and the Alarm List.

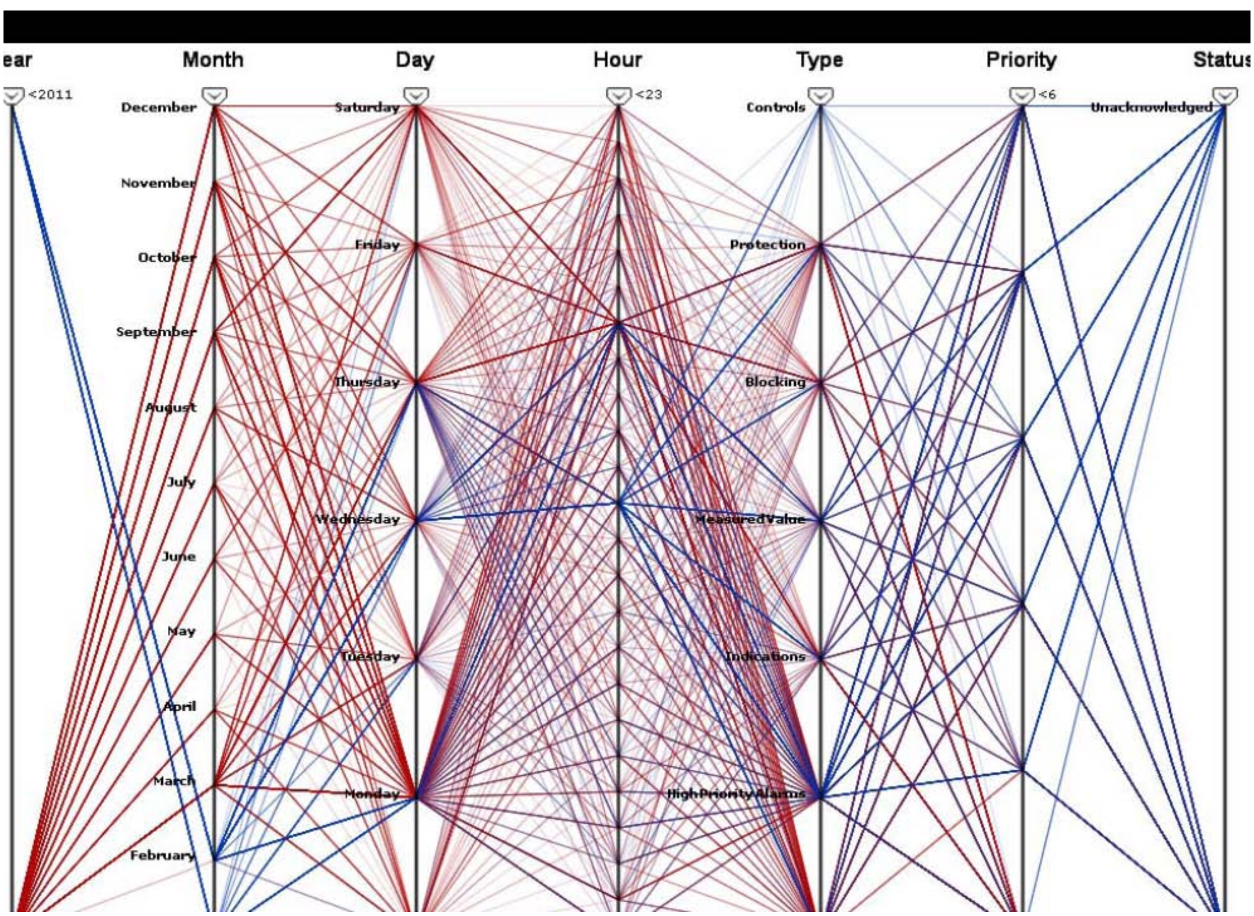

Figure 3. Parallel Coordinates representing alarms in the system. Each vertical axis represents a parameter of alarms. The lines passing through the axes represent alarms. Slider controls on each axis are used to filter alarms based on the values of the axis.

II. RELATED WORK

Siirtola has studied Parallel Coordinates and Reorderable Matrix visualizations and evaluated their use when coordinated or linked together [8]. A Reorderable Matrix is similar to a list in that its contents are symbols instead of text or numerical values. The study found coordination between the visualizations very useful in terms of reduced thinking overhead. The research also shows that the use of coordinated visualizations accelerates learning of complex user interfaces.

Cluster identification in different variants of Parallel Coordinates have been evaluated by Holten et al. [9]. The variants include the use of scatter plots, colors, opacity, smooth curves, and animation to supplement the standard Parallel Coordinates plot. It was found that with the exception of scatter plot variant, neither of the variants offered a considerable improvement.

Lanzenberger et al. have compared two InfoVis techniques namely, Stardinates and Parallel Coordinates [10]. The evaluation is based on task based user testing. The metrics for the evaluation were the task execution time for each of the visualizations. The errors from the user tasks were also used to judge the effectiveness of the techniques. Parallel Coordinates showed much better performance as compared to Stardinates.

Godinho et al. have developed a set of coordinated visualization tools called PRISMA - A Multidimensional Information Visualization Tool Using Multiple Coordinated Views [11]. The tool was evaluated through user testing. Task execution time and errors were the main metrics for the evaluation. It was concluded that the use of Parallel Coordinates does not harm the performance of user tasks and helps improve filtering and visualization if coordinated with other visualizations [11].

All the mentioned related studies, in one way or the other, evaluate Parallel Coordinates with Lists and other comparable visualizations. However, results from previous studies do not reveal how much more effective and efficient Parallel Coordinates would be than lists in filtering tasks typical to Alarm Management in industrial systems.

III. METHODOLOGY

To evaluate the effectiveness and efficiency of Parallel Coordinates over the Alarm List, an empirical, test-case based user study was conducted. The experiment aimed at finding answers to the following questions:

- How significant is the gain in terms of efficiency (time) and effectiveness (error rate) when using Parallel Coordinates compared to Alarm List for filtering alarms?
- Which visualization method do the participants prefer in terms of usability factors namely, accuracy, efficiency, learnability, memorability, satisfaction and intuitiveness?

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During the design of the prototype and while trying out the visualizations we observed that use of Parallel Coordinates made many difficult filtering tasks trivial and the amount of thinking required to finish the task was reduced. This formed the basis of our hypothesis.

A. Hypothesis

We hypothesized that use of coordinated Parallel Coordinates to filter alarms and identifying patterns in alarm data would be faster and more accurate as compared to Alarm List. The null hypothesis thus assumes that filtering does not improve when Parallel Coordinates are used.

$H0 : \mu PC = \mu AL$

$H1 : \mu PC > \mu AL$

Where:

*H*0 = *Parallel Coordinates does not improve filtering of alarms*

*H*1 = *Parallel Coordinates improves filtering of alarms*

μPC = Mean of group's performance using Parallel Coordinates

μAL = Mean of group's performance using Alarm List

B. Participants

A total of 12 participants were involved in the evaluation, eight male and four female. They were between 24 and 56 years old, median age being 26 years. The participants used computers on a daily basis and almost all of them were from Information Technology or Engineering background. Some of the participants had background knowledge about the context of application but had not used these visualizations before.

C. Test Apparatus and Setting

The prototype application for the experiment was developed using the Geo Analytics and Visualization (GAV) framework [12], [13]. It runs on a desktop computer with displays set up similar to a real set up. The computer had large (17 inch), high-resolution (1280x1024 pixels), dual screens to show the visualizations side-by-side and was fast enough (Intel Pentium-IV 2.0 GHz) to instantaneously respond to user's actions. The experiment was recorded on video to capture participants' comments and actions while at the same time two experimenters timed the task execution and took notes as the participants performed the tasks.

D. User Tasks

The participants were required to do two types of tasks, *selection* and *filtering* for Alarm List and Parallel Coordinates. Tasks consisted of sub-tasks like *sorting* for the Alarm List and *reordering* the axes in the Parallel Coordinates.

There were two similar blocks of 11 tasks each (22 in total). Tasks were designed so that they have an equivalent and corresponding task for both Alarm List and Parallel Coordinates visualizations. This was done to ensure that both the visualizations are tested against the same use cases so their results can be compared.

The order in which participants performed tasks on the two visualizations was balanced to prevent skewed results (half of the participants performed tasks on the Alarm List first and then Parallel Coordinates, while the other half performed the tasks on Parallel Coordinates first). Tasks appeared in random order inside each block.

The tasks were categorized by their difficulty into groups based on the number of parameters involved and the steps needed to perform them correctly. Table I shows tasks used in the experiment. To accomplish a task, participants had to highlight alarms in the alarm list by selection or obtain a reduced set of alarms by filtering in the Parallel Coordinates.

Table I LIST OF TASKS USED IN THE EXPERIMENT.

Easy tasks	
Task 1	Highlight all the Alarms that occurred from March 2009 to May 2009.
Task 2	Highlight all the Alarms that occurred during May 2009 and have Priority 5 or higher.
Task 3	Highlight all the Alarms that occurred for the month of March 2009 with maximum Priority.
Moderate tasks	
Task 4	Highlight all the Alarms that occurred for the month of April 2009 with Priority 5 or higher and are Unacknowledged.
Task 5	Highlight Alarms of type ”Spontaneous Breaker Trip” having Priority 2.
Task 7	Highlight all the Alarms for the month of March 2009 with type ”Protection” having the highest Priority.
Task 8	Highlight all the type ”Control” Alarms for the month of March 2009 that are Unacknowledged, with Priority 3 or higher.

Task 9	Which Stations (Source) have currently the most number of high Priority, Unacknowledged Alarms?
Task 10	Which Stations (Source) have currently the most number of type ”Protection” Alarms and are Unacknowledged?
Difficult tasks	
Task 6	Highlight Alarms that are Unacknowledged, are of type ”Controls” and have minimum Priority.
Task 11	In April 2009 which Station (Source) got minimum ”Control” Alarms with Priority 3 or higher?

E. Evaluation Criteria

Since this study essentially focused on design and evaluation of an Alarm Management solution, metrics in EEMUA [4] were considered in the experiment design. Although EEMUA metrics were not used in their entirety, the experiment utilized parameters such as operator response times and use of questionnaires in a similar fashion as in a real world case. The following parameters were recorded during the experiment:

- Task Execution time (efficiency)
- Error rate (effectiveness)

Participants were asked to fill in a questionnaire to obtain subjective information such as accuracy, speed, learnability, memorability, efficiency, satisfaction and errors. Answers were recorded on a Likert scale by the participants. Another reason for using such a questionnaire was to capture the participants’ perceived notion of the visualizations’ characteristics like speed and accuracy. Answers from the questionnaire served as a verification of the observations from the experiment.

F. Test Protocol

Each participant was briefed about the evaluation procedure before the test. The experiment supervisor gave a 15-20 minutes introductory presentation to each participant about the motivation and context of the study, the two visualization methods and their use, and the tasks in order to familiarize him/her to the system equally. The participant was asked to perform some sample operations to get familiar with the prototype and ’think aloud’ during the procedure. When the participant indicated being familiarized with the use of the prototype, the actual tests were conducted.

Saad bin Azhar and Mikko J. Rissanen. Evaluation of Parallel Coordinates for Interactive Alarm Filtering. In: Proceedings of the 15th IEEE International Conference on Information Visualization (IV), London, UK, July 13-15, 2011, pp. 102–109. IEEE. DOI: 10.1109/IV.2011.30

The test was conducted with each participant one by one and observed by two experimenters. The experimenters took notes, recorded execution times and errors for tasks, recorded the verbal communication and interviewed the participant for feedback after each test.

At the completion of the test, the participants were asked to fill out the questionnaire to acquire demographic information, their preferred technique in each task, the difficulties they had with each of the visualizations. The experiment took 50 to 70 minutes to perform all the tasks by one participant. The mean duration was 60 minutes. The participants were asked to execute the tasks as quickly as they could manage but with the aim of getting the right answers. Figure 4 shows the filtered Parallel Coordinates visualization similar to one of the evaluations.

A pilot test was conducted to check the clarity, completeness and impartiality of the testing protocol. The test design was iterated based on the findings from the pilot test before the actual evaluation was conducted. Results of the pilot test were omitted from the final analysis.

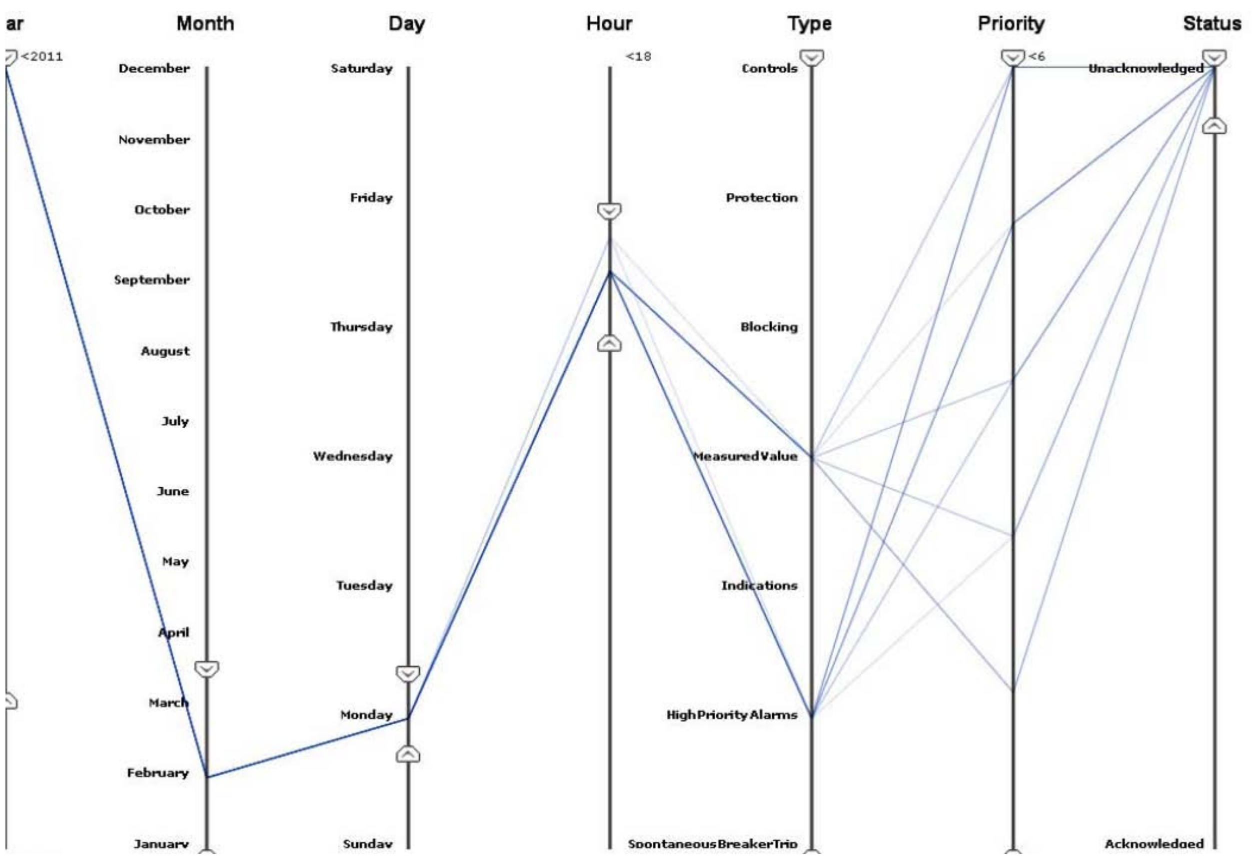

Figure 4. A view of the Parallel Coordinates plot with some alarms filtered to show unacknowledged alarms from first quarter of 2011, occurring on Mondays between 15:00 and 18:00. The Alarm List corresponds to this filtering and is reduced automatically to show only the alarms which match these criteria.

Saad bin Azhar and Mikko J. Rissanen. Evaluation of Parallel Coordinates for Interactive Alarm Filtering. In: Proceedings of the 15th IEEE International Conference on Information Visualization (IV), London, UK, July 13-15, 2011, pp. 102–109. IEEE. DOI: 10.1109/IV.2011.30

IV. RESULTS

The most pressing evidence was found in the task execution time per task together with the reduced number of errors. Figure 5 shows the mean, minimum and maximum execution times per task for Alarms List and Parallel Coordinates for all 12 participants and 11 tasks. Figure 6 summarizes the right and wrong answers for the same.

The results showed that there is indeed an improvement in the effectiveness and efficiency of the tasks performed when Parallel Coordinates were used. Use of Parallel Coordinates enhanced filtering and pattern analysis.

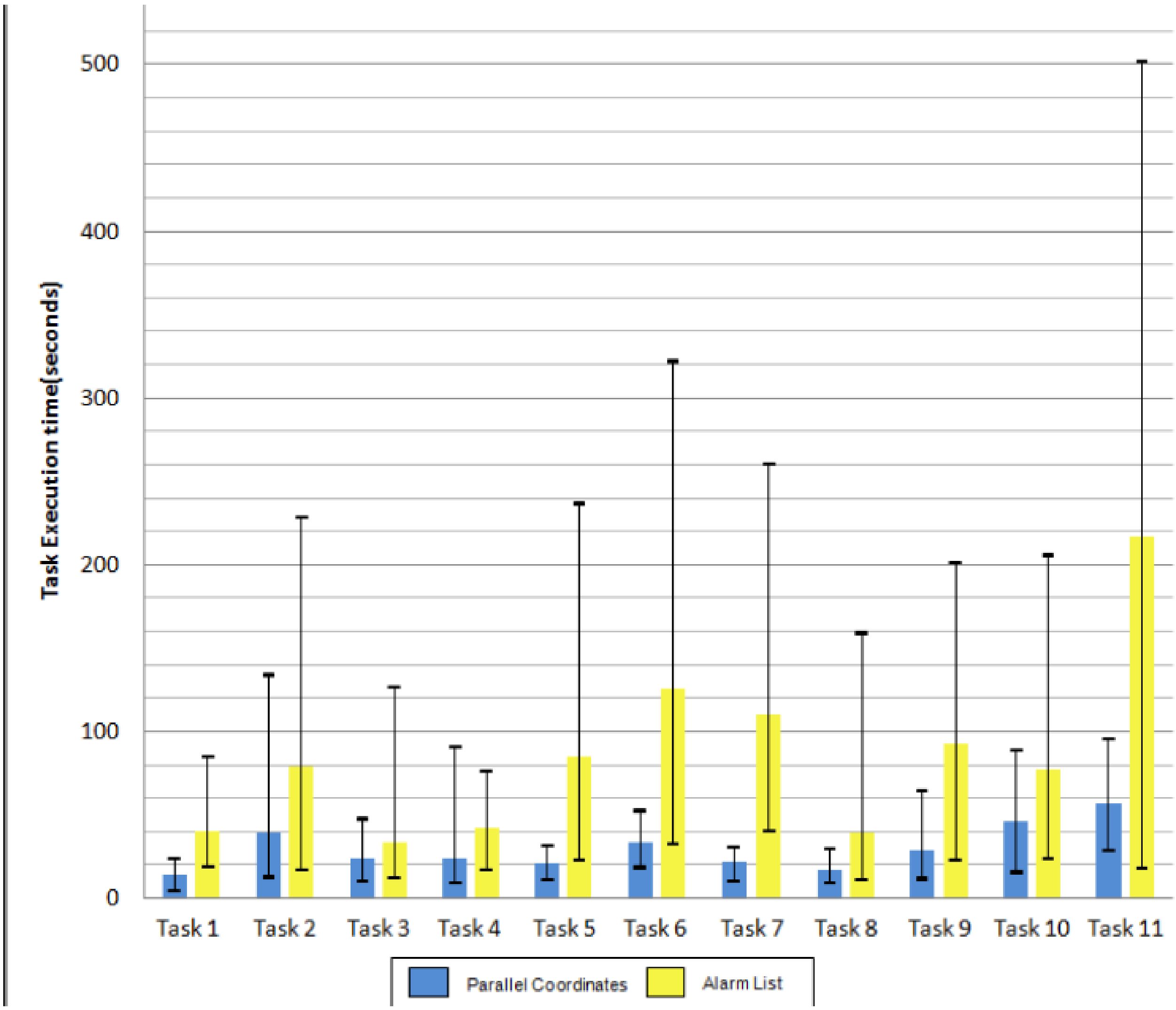

Figure 5. Mean task execution times on Parallel Coordinates and Alarm List for all tasks. Parallel Coordinates have shorter executing times on average.

Saad bin Azhar and Mikko J. Rissanen. Evaluation of Parallel Coordinates for Interactive Alarm Filtering. In: Proceedings of the 15th IEEE International Conference on Information Visualization (IV), London, UK, July 13-15, 2011, pp. 102–109. IEEE. DOI: 10.1109/IV.2011.30

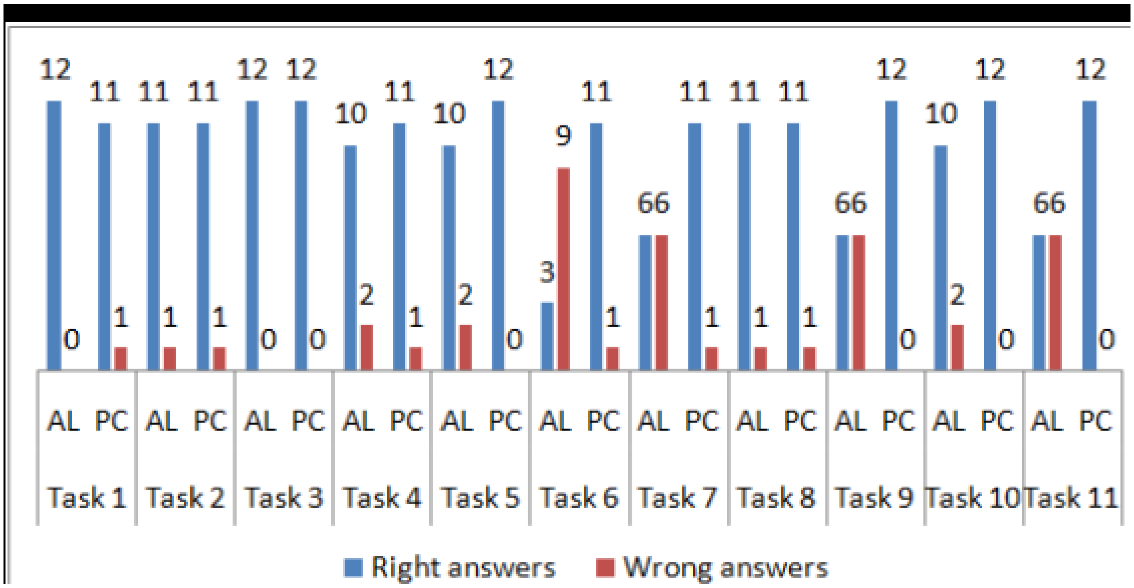

Figure 6. Number of right and wrong answers for each task using Alarms List(AL) and Parallel Coordinates(PC). Parallel Coordinates produced lesser wrong answers to tasks.

A. Task Execution Times per Task Difficulty

The participants performed better with the Parallel Coordinates in general. The task execution time using filtering on Parallel Coordinates was 392.82 seconds (61.5% faster) on average. Figures 7, 8 and 9 represent box plots of task execution time for easy, moderate and difficult tasks respectively.

The observations for task execution times for the two groups (Parallel Coordinates and Alarm List) were statistically analyzed using single factor ANOVA. The analysis indicated that there is a significantly high efficiency gain in terms of task execution time for difficult tasks ($p<0.01$) while for the simple and moderate tasks there was a marginally significant gain ($p<0.1$) with moderate tasks having relatively higher performance gain as compared to easy tasks.

Comparing Alarm List and Parallel Coordinates, the results for difficult tasks namely, Tasks 6 and 11 both had a 73.7% decrease in mean task execution time with a drop in standard deviation from 79.6 to 10.3 for Task 6 and 130 to 22 for Task 11. The mean drop in task execution time for moderate tasks ranged from 40-80% when Parallel Coordinates were used. The standard deviation in execution times for moderate tasks shows that there was a considerable improvement in general. Among easy tasks, Tasks 1, 2 and 3 had 64%, 49% and 28% lower executions times in case of Parallel Coordinates with standard deviations lowered to 5.5, 32.8 and 13.2 respectively.

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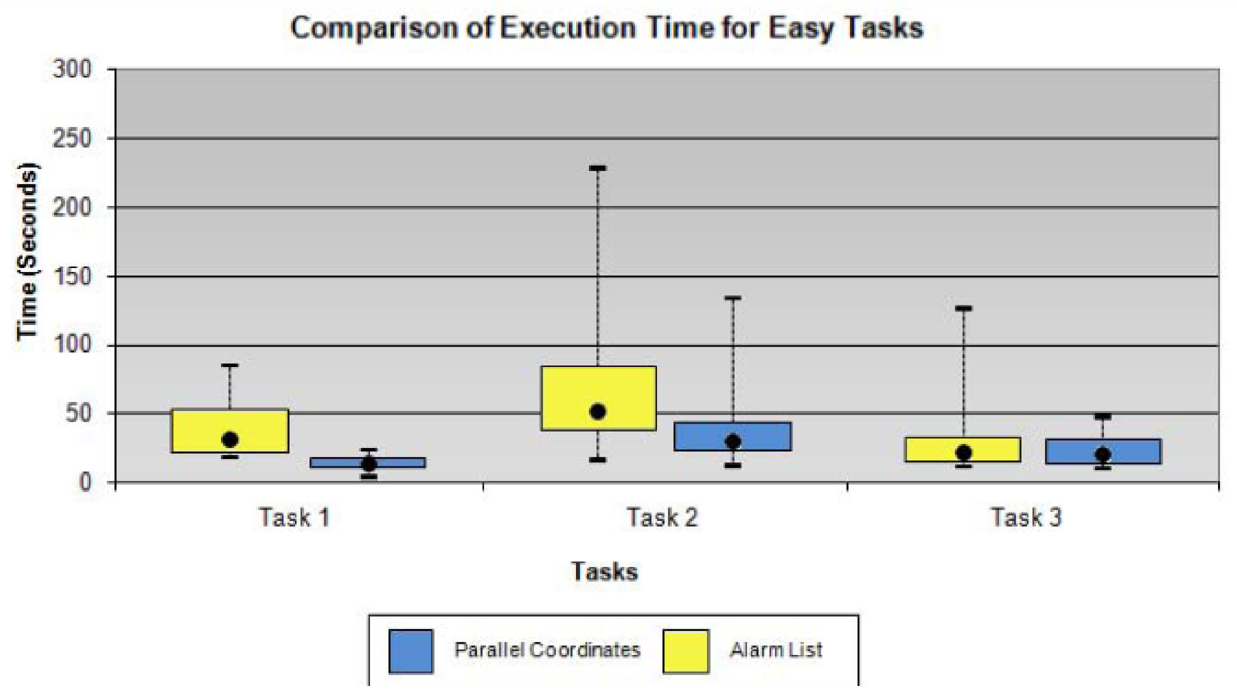

Figure 7. Task execution times (n=12 for each) for easy tasks. Parallel Coordinates do not offer considerable improvement from Alarm List.

Saad bin Azhar and Mikko J. Rissanen. Evaluation of Parallel Coordinates for Interactive Alarm Filtering. In: Proceedings of the 15th IEEE International Conference on Information Visualization (IV), London, UK, July 13-15, 2011, pp. 102–109. IEEE. DOI: 10.1109/IV.2011.30

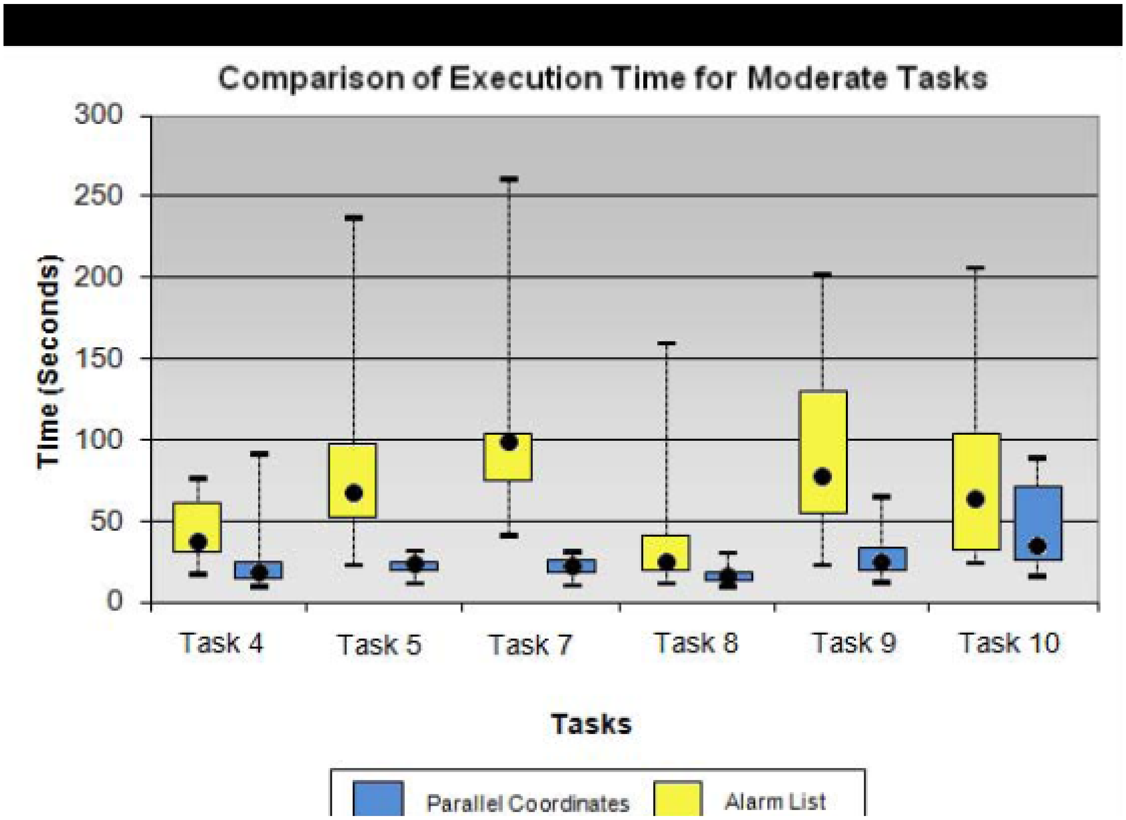

Figure 8. Task execution times (n=12 for each) for moderate tasks. There is a marked decrease in execution times when Parallel Coordinates were used.

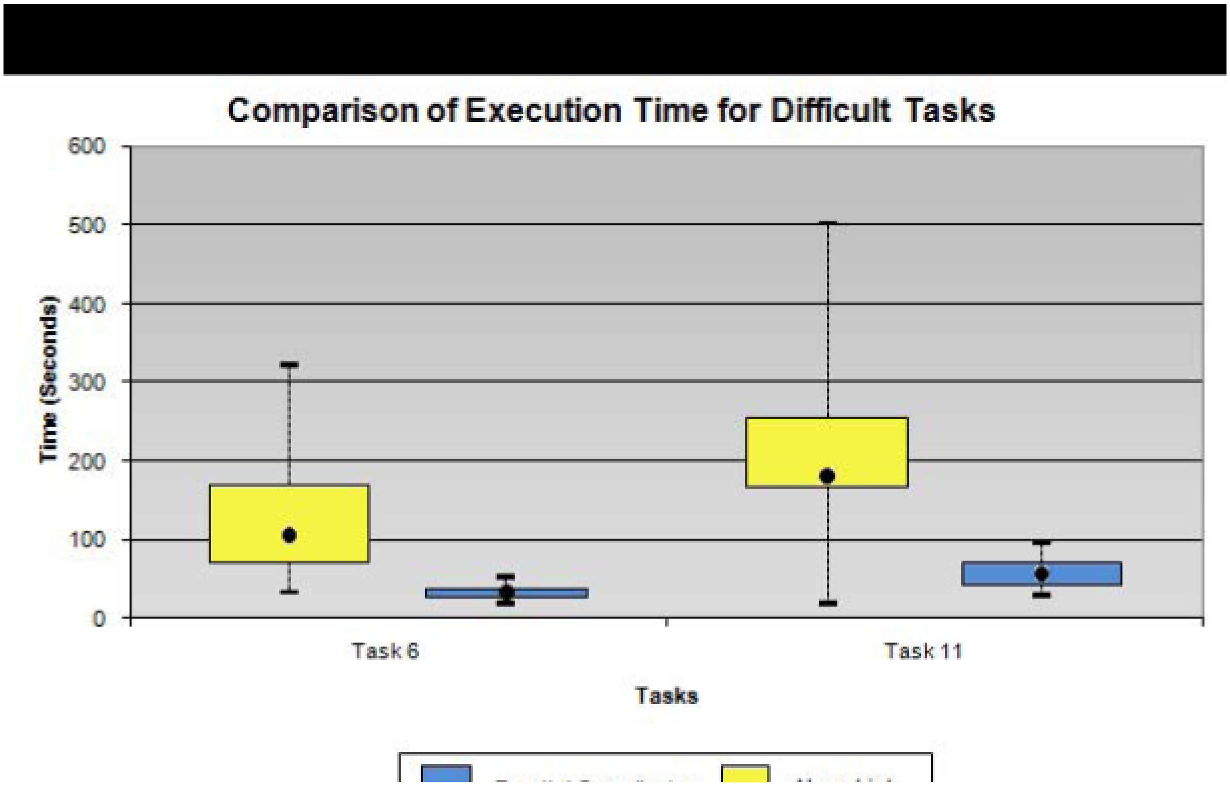

Figure 9. Task execution times (n=12 for each) for difficult tasks. Parallel Coordinates have highly significant effect on the filtering tasks in terms of execution time.

B. Error Rate

Out of the 132 tasks performed by total 12 participants, Parallel Coordinates produced 29.9% (126 as compared to 97 right answers) more correct answers than Alarm Lists. The error rate was reduced by 4.8% (6 as compared to 35 wrong answers) when Parallel Coordinates were used. Figure 10 represents the total right and wrong answers by participants on the Alarm List and Parallel Coordinates.

Saad bin Azhar and Mikko J. Rissanen. Evaluation of Parallel Coordinates for Interactive Alarm Filtering. In: Proceedings of the 15th IEEE International Conference on Information Visualization (IV), London, UK, July 13-15, 2011, pp. 102–109. IEEE. DOI: 10.1109/IV.2011.30

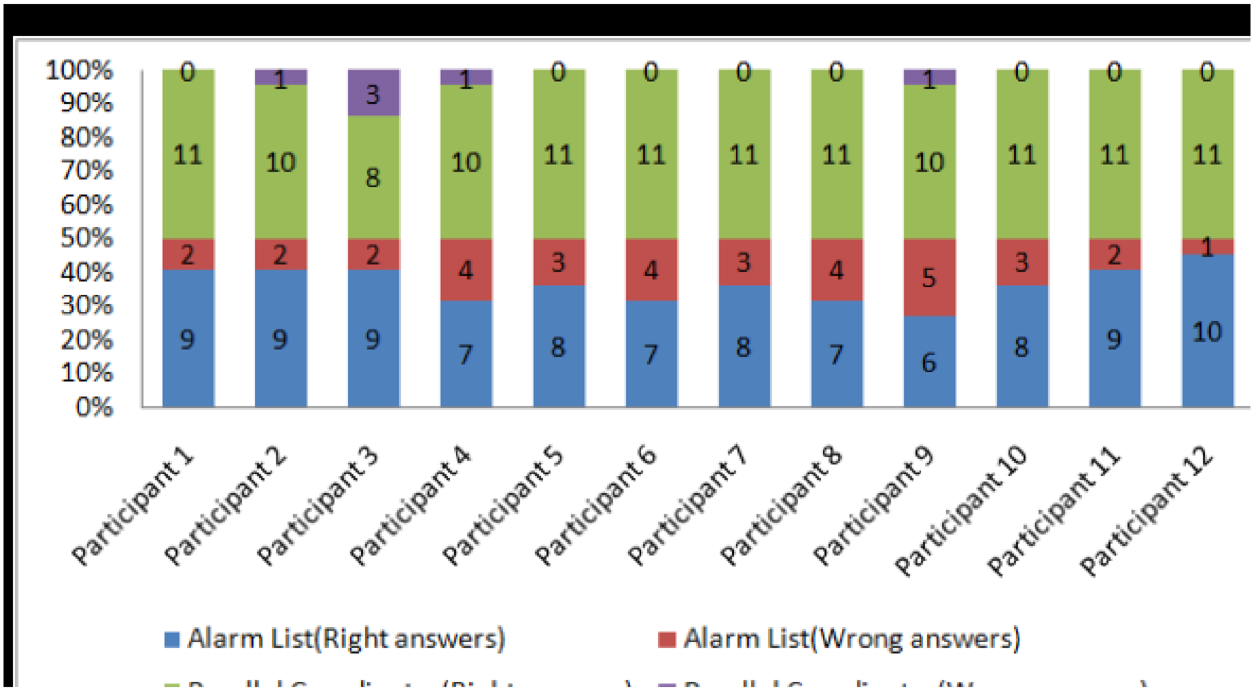

Figure 10. Number of right and wrong answers per participant (n=12) for both the Alarm List and Parallel Coordinates.

C. Subjective Satisfaction

Apart from the findings from the quantitative evaluation, the participants expressed subjective satisfaction on the questionnaire. Participants found the use of Parallel Coordinates faster, more intuitive, more accurate, easier to learn and remember, more supportive of pattern identification as compared to Alarm Lists. Figure 11 shows the findings of the questionnaire on participants' perceived notion of factors such as speed, accuracy, intuitiveness for Alarm List and Parallel Coordinates respectively.

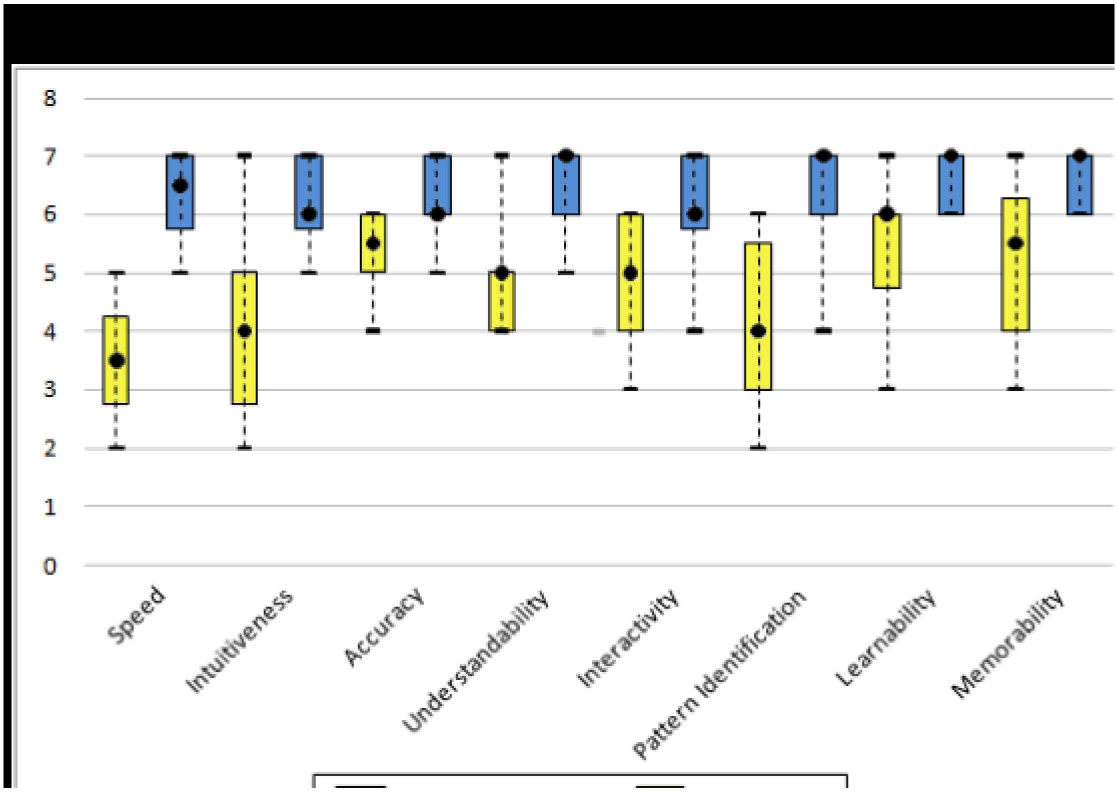

Figure 11. Participants perception of the Alarm List and Parallel Coordinates visualizations on a scale of one to seven, seven being highest.

D. Learning Effect

There was no considerable effect of learning on the participants' performance i.e. the order in which the participants used the Parallel Coordinates or the Alarm List, did not affect their performance on either visualization. Although the questionnaire results revealed that the participants preferred using Parallel Coordinates, statistical results show that their performance on either of the visualizations did not improve or reduce due to the order they performed tasks.

V. DISCUSSION

The results obtained from the evaluation were strongly in favor of use of Parallel Coordinates for Alarm filtering. Among the three categories of tasks, the increase in efficiency was not very high for easy tasks. The underperformance of Parallel Coordinates in Task 3 was thought to be attributed to one participant's extensive experience on working with list based visualizations on normal office applications, namely MS Excel. Only this one participant showed a tendency of having some difficulty in learning the use of Parallel Coordinates. The participant also had problems in the previous Task 2, but managed later tasks better.

For Parallel Coordinates in general, moderate and difficult tasks showed higher performance gain in terms of execution time. These results are representative of the reduced complexity of task execution in terms of execution time as well as thinking overhead for the participants. Overall, it can be said that the use of Parallel Coordinates improved the effectiveness and efficiency of filtering tasks which is supported by the alternative hypothesis as asserted by the statistical evaluation.

A limitation to this study was the scope of the experiment conducted. It should be investigated if more participants and a thorough and larger set of tasks will lead to more accurate results ($p<0.01$ for all tasks). Also, specific differences between various domains within the industry were not addressed in this study which are, e.g. number of priority levels and parameters in general, typical time interval between alarms and geographical distribution of alarms. The results here, however, demonstrate the advantages of Parallel Coordinates in alarm filtering tasks.

VI. CONCLUSIONS AND FUTURE WORK

This study evaluated Parallel Coordinates against conventional Alarms List for filtering and visual pattern identification of alarms. It was observed that it is in fact more efficient and more effective to use Parallel Coordinates. Use of Parallel Coordinates made it easier to perform difficult tasks in particular that consisted of multiple parameters. For easy tasks, performance gain was smaller. Thus we claim that Alarm Management in industrial applications could benefit from having Parallel Coordinates as the interface for filtering alarms and identifying patterns in alarm data especially when there are complex or difficult tasks at hand.

Future work covers a real world validation as a longitudinal study with operators in a real control room environment in e.g. electricity distribution or production plants using a full set of EEMUA metrics for alarm management.

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