Multiple Coordinated Information Visualization Techniques in Control Room Environment

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ABSTRACT

Presenting large amount of Multivariate Data is not a simple problem. When there are multiple correlated variables involved, it becomes difficult to comprehend data using traditional ways. Information Visualization techniques provide an interactive way to present and analyze such data.

This thesis has been carried out at ABB Corporate Research, Västerås, Sweden. Use of Parallel Coordinates and Multiple Coordinated Views was suggested to realize interactive reporting and trending of Multivariate Data for ABB’s Network Manager SCADA system.

A prototype was developed and an empirical study was conducted to evaluate the suggested design and test it for usability from an actual industry perspective. With the help of this prototype and the evaluations carried out, we are able to achieve stronger results regarding the effectiveness and efficiency of the visualization techniques used. The results confirm that such interfaces are more effective, efficient and intuitive for filtering and analyzing Multivariate Data.

Keywords: Multivariate Data, Information Visualization, Parallel Coordinates, Stacked Graphs, Multiple Coordinated Views
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Last but not the least, we would like to thank Tobias Åström, Chief Research Engineer and Sara Johansson, PhD of the National Center for Visual Analytics (NCVA) at the Linköping University, Sweden for their support on the GAV Framework.
# ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>HCI</td>
<td>Human Computer Interaction</td>
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<td>HiD</td>
<td>High Dimension</td>
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<td>HMI</td>
<td>Human Machine Interface</td>
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<td>IIR</td>
<td>Interactive Information Retrieval</td>
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<td>InfoVis</td>
<td>Information Visualization</td>
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<td>MCV</td>
<td>Multiple Coordinated Views</td>
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<td>MD</td>
<td>Multivariate Data</td>
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<td>NM</td>
<td>Network Manager</td>
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<td>PC</td>
<td>Parallel Coordinates</td>
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<td>WS500</td>
<td>Work Station 500</td>
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## CONTENTS

ABSTRACT .................................................................................................................................. 1
ACKNOWLEDGEMENTS ............................................................................................................. 3
ABBREVIATIONS ...................................................................................................................... 5
1. INTRODUCTION .................................................................................................................. 9
  1.1. Context and Industry Application .................................................................................. 9
  1.2. Thesis Outline .............................................................................................................. 10
2. BACKGROUND ................................................................................................................... 11
  2.1. Process Control Applications ....................................................................................... 11
  2.2. Control Room Requirements ....................................................................................... 12
  2.3. Network Manager ......................................................................................................... 12
  2.4. WS500 Human Machine Interface ............................................................................... 13
3. PURPOSE AND MOTIVATION .......................................................................................... 15
  3.1. Background .................................................................................................................. 15
  3.2. Problem Statement ....................................................................................................... 16
  3.3. Aims .............................................................................................................................. 16
  3.4. Objectives .................................................................................................................... 16
  3.5. Research Questions ...................................................................................................... 16
  3.6. Research Methods ....................................................................................................... 17
4. GRAPHICAL REPRESENTATION OF DATA .................................................................. 19
  4.1. Types of Data ................................................................................................................ 19
  4.2. Information Visualization ............................................................................................. 20
  4.3. Lists .............................................................................................................................. 22
  4.4. Stack Graph .................................................................................................................. 22
  4.5. Choropleth Maps .......................................................................................................... 23
  4.6. Parallel Coordinates ..................................................................................................... 23
  4.7. Multiple Coordinated Displays ................................................................................... 25
  4.8. Related Work ............................................................................................................... 26
    4.8.1. GeoAnalytics Visualization (GAV) Framework .................................................. 26
    4.8.2. PRISMA .............................................................................................................. 27
    4.8.3. Lanzenberger et al’s Work .................................................................................. 28
    4.8.4. Siirtola’s Work .................................................................................................... 28
5. VISUALIZING NETWORK MANAGER INFORMATION .............................................. 31
  5.1. Alarms and Events ....................................................................................................... 31
  5.2. Patterns and Trends ...................................................................................................... 32
  5.3. Interactive Information Retrieval .................................................................................. 32
6. METHODOLOGY ............................................................................................................... 35
  6.1. Analysis and Study ....................................................................................................... 35
    6.1.1. Initial Investigative Study ..................................................................................... 35
    6.1.2. Requirement Gathering ........................................................................................ 36
    6.1.3. Selecting InfoVis Techniques ............................................................................... 36
  6.2. Design and Implementation of Prototype .................................................................... 36
    6.2.1. Designing the Prototype ..................................................................................... 37
    6.2.2. Prototype Implementation .................................................................................... 37
  6.3. Evaluating the Design ................................................................................................... 38
1. INTRODUCTION

In today’s industry, the quantity of data that needs to be analyzed has increased many folds and continues to do so. Industrial data contains patterns and trends about the processes in use. Quite often, this data contains relationships between more than two, three or even more variables. Such data is called Multivariate Data (MD) or High Dimensional Data. It becomes difficult to present MD on visual displays due to limitations in screen space and perception. Information Visualization (InfoVis) techniques help identification of patterns in MD.

The terms variables and dimensions have been used interchangeably throughout this text to refer to the different attributes of a Multivariate Dataset. The term Data when used separately, represents raw values that do not carry any meaning. While Information refers to the same data when it is transformed to convey some meaning, pattern or trend.

MD cannot be easily represented on standard bar charts, scatter plots or the like. Two main reasons are the high volume of data and the need to view only a limited part of the dataset at a time. Representing all the data visually may not be feasible in the first place and even if that is done, it may not be useful for a user. There is a need to filter or selectively analyze this data to make sense out of it. Visualizing data in an interactive way can make it easy to understand the cause and effect relationships quickly and clearly.

The focus of this thesis is the use of InfoVis techniques that could be employed in Control Room environments. This study attempts to find interactive and intuitive visualizations methods which help analyze the data in Power Transmission Control Rooms.

1.1. Context and Industry Application

ABB is a global supplier of power and automation solutions. They enable their customers to improve the efficiency of their systems and increase productivity. This thesis work has been conducted at ABB Corporate Research, Västerås, Sweden. It is part of a larger research project, namely CosyViz, concerning the Network Manager (NM) - ABB’s Supervisory Control and Data Acquisition (SCADA) system for managing and monitoring large electrical and gas systems - and the WS500 Human Machine Interface (HMI) to the Network Manager. These systems and their uses are discussed in Chapter 2 and 5 in detail. The research group is involved in improving the systems’ usability, interactivity and methods of InfoVis.
1.2. Thesis Outline

This section outlines the thesis structure. A brief description of each chapter and its contents is mentioned below.

**Chapter 1 (Introduction)** explains the context and industry application in which the project is carried out.

**Chapter 2 (Background)** renders the background knowledge about the thesis. It defines the necessary concepts and terms required to understand this study like, Process Control Applications, Control Room environment, Network Manager etc.,

**Chapter 3 (Purpose)** defines the research approach for carrying out the study. Starting with problem domain background, this chapter presents the research questions, research methods being used to answer these questions, aims and objectives of the study.

**Chapter 4 (Graphical Representation of Data)** provides an overview of the existing literature regarding the graphical representation of data. Multivariate data and InfoVis techniques that will be used in this study are discussed here. This chapter also provides an overview of the related work.

**Chapter 5 (Visualizing Network Manager Information)** presents the more specific details about the data in Network Manager. It is a large area to discuss therefore the focus will be on Alarms and Events.

**Chapter 6 (Methodology)** talks about the methodology adopted to carry out this research. It covers the research project lifecycle that was used throughout the project.

**Chapter 7 (Implementation)** provides details about the implementation details of the InfoVis techniques used in developing the software prototype.

**Chapter 8 (Empirical Evaluation)** illustrates the evaluation phase of the thesis. It talks about the experiment design and procedure.

**Chapter 9 (Results)** presents the findings from the study. It illustrates the qualitative and quantitative interpretations of the results carried out by empirical study.

**Chapter 10 (Discussion)** discusses the research in view of the conducted evaluations and related work. The weaknesses in evaluation and results are discussed and a text on possible improvements is presented.

**Chapter 11 (Conclusion)** draws conclusion by synthesizing the observations and results. It presents the answer to the research questions.

**Chapter 12 (Future Work)** the future work with regards to the validity of this study and suggested improvements in the design are discussed here.
2. BACKGROUND

This chapter discusses the background information, theory and context and related research for this thesis.

Process Control Applications (PCA) are usually run in Control Rooms where operators or users of the PCAs monitor and if required, control the system. One such PCA is Network Manager (NM) and its HMI, WS500.

2.1. Process Control Applications

Process Control Applications or Systems are used for monitoring and controlling large industrial processes. According to Fiset[19], these systems can fall in the following three categories:

1. **Stand-alone Units** – Simple, embedded systems performing pre-defined tasks.
2. **Distributed Control Systems (DCS)** – Usually real-time, fault tolerant systems used to control physically separate and remote parts of the overall system.
3. **Supervisory Control and Data Acquisition Systems (SCADA)** – Gather and process data about the system over long distances and provide control operations on the system. These are typically used in power transmission, oil and gas pipeline systems.

The third category, SCADA systems, will be the focus during this research as Network Manager is a SCADA application for power transmission systems. Figure 2.1 shows the HMI for a Process Control System of a furnace.

![Figure 2.1 - Process Control HMI of a Furnace [18]](image-url)
2.2. **Control Room Requirements**

Control Room applications like the one presented in Figure 2.1 have one main purpose, to present all the important variables upfront and keep the user informed about the system’s state. Additionally, SCADA systems provide the user to control certain parts of the system. The HMI for such systems should therefore be designed to suit the requirements of the system in question and its application. Fiset[19] points out that in order for a Control Room HMI to be used, its benefits should outdo the workload it adds on the operator or user.

In the context of power transmission, there are a large number of variables that need to be monitored. Data about the states of breakers, isolators, transformers and other equipment comes in every few seconds and it needs to be observed and acted upon to ensure smooth operation of the system. NM and WS500 are similar Process Control applications. Figure 2.2 shows a typical Control Room of a Power supply operator.

![Figure 2.2 – Control Room of Independent Electricity Supply Operator (Ontario, Canada) [17]](image)

2.3. **Network Manager**

Network Manager™ (NM) is a Control Room solution. It is suite of real-time SCADA applications which support Generation, Transmission and Distribution Management for large electrical and gas systems[20]. It gives the operator a Control Room interface to query information about the system’s current running state and areas of attention. NM
also provides control capabilities for operation and maintenance and rectification of faults in the power grid.

2.4. WS500 Human Machine Interface

Work Station 500 is a computer based application for Network Manager. It is basically a HMI that is used by operators to communicate with the Network Manager. This software presents huge amount of data to the operator. The data is often in the form of Alarms and Events which are related with respect to different variables like time of occurrence, type, priority and other device specific parameters. The operators have to continuously monitor this data and identify information like abnormal situations, failures and warnings.

Figure 2.3 and 2.4 show typical interfaces provided by WS500 for a power system. The former represents a substation in the power network where each component has certain attribute values displayed which can be manipulated using mouse operations. Erroneous states are represented visually by different colors and symbols. Each component has certain Alarms and Events attached to it as they occur.

![Figure 2.3 – WS500 HMI for a Electrical Station](image)

The latter interface (Figure 2.4), is list of Alarms (actionable events or notifications) raised during the operation. An alarm could be raised by an action performed on one of the components. The Alarm list in Figure 2.4 shows the existing 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 operations being carried out in the system.
3. PURPOSE AND MOTIVATION

This chapter discusses the problem statement, the aims and objectives of the research and the questions it attempts to answer.

3.1. Background

The Network Manager application and WS500 provide Control Room Operation support. Control Room operations are time critical and data intensive tasks. Large electrical grids such as those operated by power suppliers need constant monitoring and controlling. At any given time there could be hundreds or thousands of variables that have to be monitored in order to ensure smooth operation of the system. Operators need to make decisions within seconds to avoid power failures or harm to the system or personnel working on them.

Figure 3.1 – WS500 HMI for a Electrical Station

Figure 3.1 above illustrates the typical power generation system and its components with the Control Room situated in the center for monitoring and control operations. When there is huge number of events occurring simultaneously in different parts of the system, it becomes difficult to keep an eye on any specific variables. It is not easy to quickly identify the problem areas and rectify them. Even with all the information presented in a straightforward manner, it takes a hefty amount of time to filter it and identify patterns that show an anomaly in the system.
3.2. Problem Statement

The operators of the system should be able to pinpoint trouble areas and important events that occur while the system is running. Not only should they be able to get an overview of the system’s state but also identify patterns that indicate an anomalous state or one that requires action by means of human intervention. Achieving this is however very difficult in visualizations like the Alarm List presented in previous chapter. Especially when there are multiple variables involved and several thousands of sources of events, it becomes difficult to identify patterns and extract crucial information from such data. We need a way to interactively and quickly narrow down or filter the visualized data so that relationships, trends and patterns can be easily seen. At the same time it is important that we have strong evidence to support our claims for use of our suggested visualizations.

3.3. Aims

Although several attempts have been made to visualize Multivariate Data (MD) and several accepted techniques (Parallel Coordinates, Lists, Graphs etc.) exist, their specific use in Control Room environments from the perspective of usability have yet to be assessed.

The aim of this research is to come up with a solution to visualize MD in control room environments of large power systems. How do users perceive different InfoVis techniques that we have employed to visualize the data? How beneficial are these techniques in identifying patterns and trends about the system’s state? And how can multiple views of the same data improve their legibility? And above all, If we can support our arguments with valid results that certain visualization techniques are useful in the context of Control Room operations.

3.4. Objectives

The objectives of this research are three fold: (1) Choose appropriate InfoVis techniques to visualize data in power grid control systems and develop a working prototype which employs these techniques (2) Evaluate users’ perception and efficiency of the InfoVis techniques used and (3) obtain strong proof that the suggested techniques really do help solve the problem of Information Visualization in Control Rooms.

3.5. Research Questions

Since the existing system uses Lists and the suggested solution in this study is the use of Parallel Coordinates, this research will attempt to answer the following three main questions:

1. How can Multivariate Data in Control Rooms be represented efficiently using alternative techniques?
2. Does the use of filtering by Parallel Coordinates over Lists improve trend analysis of Alarms and Events?

3. Does the use of Multiple Coordinated Views facilitate the filtering tasks for Parallel Coordinates?

### 3.6. Research Methods

This research is an industry based development project which aims at finding solution to the specific problem and context defined earlier. The outcome of the research is two fold, a working prototype solution for the problem and secondly, an evaluation of the InfoVis techniques used to obtain more valid results as compared to other studies done in the same area. To answer the questions raised above, a mixed approach based on qualitative and quantitative methods has been adopted to carry out this study.

A Qualitative methodology was adopted to study the background information on InfoVis techniques, related work and the problem domain. Literature Survey was conducted by the authors while results from the initial investigative studies conducted by the CosyViz group were used for the analysis.

The evaluations were based on both quantitative and qualitative methods. The quantitative study was initiated by the result of the qualitative study conducted. The observations from literature survey and initial investigative studies (discussed in Chapter 6) formed the basis for requirements of the new prototype. The quantitative study involved empirical user tests which were conducted on the prototype to capture users’ performance and the effectiveness and efficiency of the implemented InfoVis techniques.
4. GRAPHICAL REPRESENTATION OF DATA

Information presented verbally or in the form of text reports is becoming difficult to grasp as the volume of the data grows. With verbal or text reports, it is easy to analyze one page of data but when the amount of data expands to several pages or hundreds or thousands of records it becomes nearly impossible to analyze and find patterns in it. Most people find it difficult to understand numerical representations[30]. Graphical representation makes it easier to understand the data. Using InfoVis eases location of patterns and relationships among data, improves judgment and minimizes decision making time by facilitating information processing and analogue reasoning[28].

There are several advantages of presenting data graphically, some of them are given below:

- Data contained in graphs are perceived by humans in a quick and memorable way as compared to printed data lists where the data is firstly viewed and then parsed by the brain[29]. - “A Picture is worth a thousand words”.

- Graphical representation shows the structure of the data. ‘High points’ or ‘low points’ in the graph are often necessary and help towards cognition.

- Results from graphical data can be immediately presented to the persons concerned for analysis.

- More than one variable can be easily presented in graphical form.

Depending on the type of data and the number of parameters or variables involved, we can choose from numerous different forms of representations. Some of the often used ones are Scatter Plots, Bar Graphs, Pie Charts, Histograms, Normal Distribution Curves, and Area Charts.

4.1. Types of Data

In broader terms, data can be quantitative (countable, numeric, measurable) or qualitative (non-numeric, abstract, subjective). An example of quantitative data would be the vehicle speed, number of students in a class, or GDP of a country. The opinions or perceptions of people about something, their preferences or likes and dislikes are subjective and thus are qualitative data. However, subjective data can be quantified if they are categorized or grouped.[34]

Simultaneously, data can be structured or unstructured i.e., if it has some Data Model which defines relationships or, if the data is semantically tagged or without any formation linkage. Values which are organized in fields of a database are structured data while data such as audio, video, message text or a document are unstructured data.[35]
Another way of classifying data is by its categorical nature. **Categorical** data falls under the type of quantitative data but deals with values like days of week, type of car etc. So we can say that categorical data has discrete values which may be spaced at equal intervals and normally have a non-numeric nature. This research deals with categorical data which may be both structured or unstructured.

Having said the above, data itself can be in many forms or types which Shneiderman[2] classifies as the following:

- **1-dimensional** – Linear data types such as textual reports, program source code and alphabetical list of some text are arranged sequentially. Every data type in the set is basically a line of text so that we can only measure it with its length.

- **2-dimensional** – 2-D data can be measured graphically with its length and width. For example, newspaper, geographical maps layout etc. There are two variables involved, one on each axis if it is plotted on a graph. Each variable denotes some specific domain attribute like, time, count, age etc.

- **3-dimensional** – 3-D data represents real world objects. A typical example is an object’s length, width and height. Molecules, Architectural Designs, Solid Models, and 3-D Computer Graphics fall in this category.

- **Multi-Dimensional** – Relational and statistical data having multiple attributes have to be represented in multiple dimensions. Data with \( n \) distinct attributes can be represented as a point in an \( n \)-dimensional space. The characteristics of an Element can be thought of as multivariate data where its melting and boiling points, atomic number, atomic mass, density, and number of isotopes could be some of its many attributes. The tasks in which the use of Multi-Dimensional data is involved include finding patterns, clusters, correlations among pairs of variables, gaps and outliers.

### 4.2. Information Visualization

Information Visualization (InfoVis) is the study of visual representation of data. Data can be visually represented as charts, graphs, pictures etc. It makes it easier for the viewer to interpret the data and to identify the relationships between them.

Michael Averbuch defines Information Visualization as,

> “Information visualization, an increasingly important subdiscipline within HCI, focuses on graphical mechanisms designed to show the structure of information and improve the cost of access to large data repositories. In printed form, information visualization has included the display of numerical data (e.g., bar charts, plot charts, pie charts), combinatorial relations (e.g., drawings of graphs), and geographic data (e.g., encoded maps)” [3].
Card et al. give a more concise definition of InfoVis:

“The use of computer-supported, interactive visual representation of abstract data to amplify cognition.”[1]

InfoVis deals with abstract data while Scientific Visualization deals with visualization of scientific data. Abstract data is often not physically based and hence cannot be related while Scientific data is often based on formulae and mathematical equations[1].

Employing InfoVis techniques allows the users to extract specific information in an efficient way. However, visualization of data is not a simple task especially when the data is abstract and unstructured. Moreover, this unstructured data may be categorical, in which case it may need some kind of mapping to be able to relate to other variables in the dataset. The real challenge in InfoVis is to be able to represent this data and visually identify relationships among them. Another important aspect and possible enhancement in InfoVis systems is use of interaction. Interactive systems can allow faster access to the desired view of data.

Shneiderman discusses the characteristics of a good InfoVis system according to the following tasks that a user should be able to perform[2].

- **Overview**: Overview of the entire dataset that may contain multiple variables.
- **Zoom**: Focus on a specific subset of the data.
- **Filter**: Reduction of the dataset according to specified attribute values within a dataset.
- **Details as required**: Additional data provided by an action performed by the user.
- **Relationship Management**: The ability to relate and view correlations between data items.
- **History**: A history of actions to allow backtracking.
- **Highlight**: Extraction and refinement of the dataset to get different views of the same sub-collections of the data.

When there are multiple variables involved, it is often useful to involve Multiple Coordinated Views (MCV) which show different views of the same data as the user performs one or more of the above tasks. Shneiderman presents his taxonomy of multiple window coordination and terms it as beneficial for reducing information access time, discovering unforeseen relationships and unification of multiple yet simple displays to present complex information [4].

Multiple coordinated displays will be discussed later in this chapter. However, following is a background of some of the InfoVis techniques that have been employed in this research.
4.3. Lists

Lists are used to express different kind of data items on a single plane. A list can contain both qualitative and quantitative data as well. Lists are used to partition or categorize the datasets by putting them in the separate categories. For example, a list can effectively define the attendance on a particular date of students of a specific course. Computer based lists can be sorted or grouped by different attributes. Figure 4.1 shows a typical graphical representation of a list of data from Microsoft Excel.

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</table>

Figure 4.1 - A typical list of data having multiple attributes

As indicated earlier in the problem statement, lists are difficult to sort when multiple variables are presented. Hence, it becomes difficult to visualize multiple correlated variables especially when the volume of data is high i.e., even with more than just one page of data.

4.4. Stack Graph

Stack Graphs or Stacked Area Graphs are extensions of Area Charts where each new area series is stacked upon the others. This gives a measure of the total as well as individual values of all the data series in the chart. By using this method multiple levels of information can easily be presented at once.

Figure 4.2 shows a Stacked Graph generated using VisiFire[10] tool. It shows multiple data series on the same graph. Each color in the graph represents a separate data series. Here data series are plotted against two common dimensions within the complete dataset. It can be observed that at X = 1, the total Y value is a little over 600 while at the same time the values of all the individual data series can be seen and compared.
4.5. Choropleth Maps

Choropleth Maps are used for presenting quantitative data but at the same time they provide a sense of qualitative or relative meaning to the data. These maps define patterns by using different colors or different shading for polygons classified in the same order. Figure 4.3 shows US states by population. Lower population states are presented in light green color and states with relatively high population are shown in the dark green.

![Choropleth Map of US States](image)

Figure 4.3 - A Choropleth map showing US States by population [5]

4.6. Parallel Coordinates

Parallel Coordinates (PC) were first suggested by Maurice d’Ocagne[8] in 1885 and later it was re-discovered independently by Al Inselberg and presented in his 1985 publication[6]. However, the more advanced uses of Parallel Coordinates were suggested...
by Wegman[7] that led to their use in applications such as Collision Avoidance Algorithms in Air Traffic Control, Data Mining, Optimization and Process Control.

Using Parallel Coordinates allows presenting more than 3 orthogonal axes on a 2-D plane. It is best suited when there is a requirement for displaying or analyzing High-Dimensional (HiD) geometry or Multivariate Data (MD).

![Parallel Coordinates Diagram](image)

**Figure 4.4 – Representation of Multivariate Data on Parallel Coordinates**

Figure 4.4 shows how multi-dimensional data is represented on a Parallel Coordinates plot. As the name suggests, a Parallel Coordinate plot contains an axis for each of the variables placed in parallel to each other either horizontally or vertically. The values on the axes range between the minimum and maximum values of the corresponding variable in that dataset. Instead of making a point in an *n*-dimensional space, PC represents each of these points as a line through all (*n*) axes. A line intersects an axis at the point where it matches the value of the corresponding variable. This way there could be as many lines as the number of data points.
Figure 4.5 shows a Parallel Coordinate plot of MD from cars. There are six variables, each representing a particular attribute about the car. This plot was generated using the GAV Framework[11] for visualization of Multivariate Data.

An enhancement in the traditional Parallel Coordinates is the use of color gradients as seen in Figure 4.1. Usually 15 gradients are used which range between two colors. Each segment of a line is given a different gradient depending upon its magnitude on the axis. [7] If the lines connecting two consecutive axes \(A_1\) and \(A_2\) do not cross each other, then it means that the two axes are positively correlated. However, if the lines cross, the two axes are negatively correlated. By positive correlation between two axes we mean that the two variables increase or decrease together if one of them changes.[33]

### 4.7. Multiple Coordinated Displays

In a typical display where a single graph or view is used to show data, it is difficult to analyze Multivariate Data. It is best that such data is shown through a number of different visualizations. Each technique or method used, highlights different trends and patterns in the data. Though there is no best combination of these methods, however, the choice depends on the context and need of the problem at hand. Baldonado[21] et al. present eight rules which help design Multiple Coordinated Views (MCV) by giving guidelines on how to select a visualization method and how to present data and design the interaction of the views.

Coordination between these multiple displays presents an opportunity for interactive inquiry methods also known as Visual Inquiry (VI) or Visual Analytics (VA). VA allows
the user to perform ‘selection’ and ‘navigation’ tasks on the data in one view and be able to see the corresponding results in a different view of the same data. Shneiderman describes Selection and Navigation as the main operations in coordinated views. Selecting an item in one view can either result in selection or navigation in another view. Navigating can result in navigation in other coordinated views [4].

The GAV Toolkit[11] presents another powerful action for coordinated views – Filtering. By using Parallel Coordinates with multiple linked views, filtering can be performed simultaneously in different views of data to facilitate the analysis. Figure 4.6 shows a view of the GeoWizard[11] application developed using the GAV Toolkit. It demonstrates the use of multiple linked view and filtering using Parallel Coordinates.

![Figure 4.6 – The GeoWizard application’s multiple linked views](image)

4.8. Related Work

There have been many attempts to visualize data with multiple variables and simplify overpopulated plots. Among them, some have focused on filtering and reducing the size of the displayed data set while others provide an overview of the complete data. Coordinated linked views are also an active area of research. The following studies, though not dealing with Power Transmission Systems, are related to this research in their use of InfoVis techniques.

4.8.1. GeoAnalytics Visualization (GAV) Framework

Led by Mikael Jern at National Center for Visual Analytics, Linköping University, the GAV Framework[11] is a recent attempt to interactively visualize geographically referenced Multivariate Data. The research focuses of Multiple Linked Views for
InfoVis. In their research work, they have developed a set of visualization tools including a Parallel Coordinates plot, Table Lens and Choropleth Map for interactive visualization. The framework provides linking, selection and filtering support for dynamic, visual inquiry. The main aims of the research were to develop InfoVis techniques which provide[11]:

- A combination of visual representation of data and visual interfaces.
- A representation of data from different perspectives which are dynamically linked and coordinated.
- Interactive interface to perform Visual Analytics and reasoning.
- Methods to identify trends and patterns in the data.
- Intuitive and usable design to perform tasks and solve problems.
- Use of different approaches, understanding the tradeoffs between them and using the more reasonable methods to find solutions to problems.

The GAV framework has been used in several studies. The research team has explored and analyzed large Geo-Spatial datasets. Examples include the Social Sciences data about Sweden’s municipalities[12,13] and visualizing 4D oceanographic volume data[14].

### 4.8.2. PRISMA

Godinho et. al have developed a set of coordinated visualization tools in Java called PRISMA - A Multidimensional Information Visualization Tool Using Multiple Coordinated Views[15]. The guidelines for the conception PRISMA are summarized below:

- An easy to use interface for user tasks.
- Possibility of visualizing any dataset in the implemented visualization techniques (Treemap, Parallel Coordinates, and Scatter Plot).
- Interaction with the visualized data in more than one visualization technique both individually and simultaneously.
- Coordination between the InfoVis techniques.

The tool has been evaluated by user testing. There were four user tasks which were evaluated on the execution time and their wrong or right answers. The researchers conclude that the use of Parallel Coordinates does not harm the performance of user tasks and helps improve filtering and visualization if coordinated with other views[15].

However, the comparison made between the performance of “General Users” and “Computer Professionals” in the study seem illogical. Even more astonishing is the result that general users outperformed computer professionals on the tasks. This seems improbable and considering the evaluation protocol, both users should have performed comparably at least at some of the tasks.
4.8.3. Lanzenberger et al’s Work

Lanzenberger et al. have compared two InfoVis techniques namely, Stardinates and Parallel Coordinates[16]. The evaluation is based on user tasks. The activity was recorded and compared by the minimum, maximum and average time it took to answer a question using each of the visualizations. The number of correct answers from the users was also used to judge the effectiveness of the techniques.

The results conclude that Stardinates are more effective as compared to parallel Coordinates in this context where highly structured data like Psychotherapeutic data of patients is being analyzed. However, we see that displaying Stardinates for five patients’ data requires more screen real estate as compared to Parallel Coordinates. It is possible to process only a limited number of Stardinates at a time while a Parallel Coordinates plot can display a lot more data in the same space. The use of both of these techniques is thus a tradeoff between efficiency and the amount of data that can be processed.[16]

4.8.4. Siirtola’s Work

Siirtola has combined Parallel Coordinates and Reorderable Matrix visualizations and evaluated their use in a coordinated setting[22]. A Reorderable Matrix is very similar to a List where its contents are symbols instead of text or numerical digits, each column represents a record and each row refers to a variable in the records. Figure 4.7 shows the Parallel Coordinates plot and Reorderable Matrix used by Siirtola.

![Figure 4.7 - Parallel Coordinates and Reorderable Matrix of same data [22]](image)

The dataset used in this empirical study was randomly generated and had general names to remove the dependency from domain knowledge. The research does not strongly support the effectiveness of one approach over the other. However, the participants of the
study found the linking very useful. Using conceptually different views of the same data reduced the cognitive load of the users. The research also concludes that the use of coordinated views accelerates the learning of complex user interfaces.
5. VISUALIZING NETWORK MANAGER INFORMATION

Having set forth the requirements of Process Control Applications and presented the background of Network Manager, WS500 and InfoVis, it is easier to understand their context specific use in the research.

In power transmission systems there are usually a large number of inputs and outputs attached to sensors and control loops which send out data to Control Room Applications (Network Manager and WS500 in this case). This data are system messages about current activity such as voltage or power levels going up or down a defined limit, a malfunction in a component or just a notification that represents normal system operation.

In the context of Network Manager, this data is in the form of ‘Alarms’, ‘Events’, different data points and other measurements. The task of the operators in the control rooms is to analyze this data and ensure smooth system operation by taking corrective actions if a problem is indicated. A lot of the information passed by Network Manager to WS500 is in the form of Alarms and Events. Hence the focus of this research would be to visualize Alarms and Events and it is best that we describe them here.

5.1. Alarms and Events

Alarms and Events are notifications of system activity. They represent information about stations and sub-stations down to component level like isolators and breakers. Both Alarms and Events can belong to a Category, Priority and Type and provide the Source Station, Time and Message. It is important to know about these attributes, however, their details are not relevant in this study.

At any point in time, an operator may be looking at a couple of hundred to several thousands of Alarms and Events. Searching through these Alarms and finding patterns that indicate critical system state takes a lot of time. The current method of displaying these Alarms does not support searching and interactive filtering. A user would typically select an Alarm from the list and perform an action on the details view. Figure 5.1 shows the existing “Alarm List” function of WS500.
5.2. Patterns and Trends

Identifying patterns and trends in a bulky list of alarms is practically a difficult task. The operators need to query data and find information such as:

- If a particular station or region has a considerable number of Alarms.
- If there are any Alarms, what Category, Priority or Type they belong to?
- What is their frequency?
- Do they occur at specific times or are they just random?
- What time of day, week, month or year do Alarms mostly occur?
- How many high priority Alarms occurred during last weekend?

There could be many scenarios like these which if answered quickly, can identify trends in the system activity and help optimize the operation.

5.3. Interactive Information Retrieval

The Alarm List shown in Figure 5.1 does not allow any sort of interactive querying, sorting or filtering. If the operator is able to interactively filter and narrow down the Alarm List, she will be able to identify patterns in the data easily. An Interactive
Information Retrieval (IIR) system as described by Marchionini[23], has the following properties:

- The system should aim to get people closer to the meaning of information they need and not just present the information.
- It should support increased user responsibility so the user can exercise control and use intellect to get to the desired information.
- It should have a flexible architecture for adaptation to demands over time.
- It should aim at preserving the relation between personal and shared memories and tools rather than providing discrete standalone services.
- It should support the entire life cycle of information from creation to preservation instead of only the use or dissemination of information.
- It should support tuning by information professionals or by end users to add value to its resources.
- It should provide a good user experience.

This research evaluates use of Parallel Coordinates and Multiple Coordinated Views for interactive analysis of Alarm and Events. With multiple variables in these Alarms and Events, it becomes very difficult to identify patterns in the list when the data exceeds even one page. As the number of variables increase, the use of IIR systems present an opportunity to optimize the information retrieval methods. Ahlberg and Shneiderman [24] describe these interactive methods as “dynamic queries”. They define these systems to have the following characteristics:

- Visual representation of the query’s parameters or components using buttons or range sliders or other UI objects.
- Visual presentation of the results of the query.
- Selection by pointing, not typing.
- Immediate and continuous response for queries (typically within 100ms).
- Rapid incremental and backtracking actions for querying.
6. METHODOLOGY

The methodology adopted to carry out this research. The thesis work mainly comprised of the following three phases:

1. Analysis and study of problem
2. Design and implementation of prototype
3. Evaluating the design

The lifecycle of this research project is shown in Figure 6.1. The dashed outline shows the scope of this study and the dashed arrows to previous phases show iterations to improve upon the initial design and implementation. Part of the analysis was done by the rest of the research group and was the input to this study.

Figure 6.1 – Research Project lifecycle

6.1. Analysis and Study

The analysis and study work is carried out with qualitative method of research and it is based upon the following sub tasks:

1. Initial Investigative Study
2. Requirement Gathering
3. Selecting InfoVis Techniques

6.1.1. Initial Investigative Study

In the analysis phase, some investigative studies were conducted by other members of the research group to find out possible areas of improvement within interaction, usability and visualization. These were mainly interviews and observations done in real Control Room environment, with actual operators of the current NM and WS500 systems. Operators were observed in their work environment to see how they performed certain tasks. Later, the operators were interviewed. They were asked a series questions to get
their opinion on the strong and weak areas of the system. These questions also covered aspects which were not covered during the observations.

The results of the study were the basis of this research. The study pointed out several problems in the existing system. The findings of the study were the input to use case scenarios, which led to the development of low fidelity (Lo-Fi) prototypes. These Lo-Fi prototypes were suggested after doing evaluation of existing InfoVis techniques and selecting appropriate ones from them.

### 6.1.2. Requirement Gathering

A main part of the requirements comes from the investigative studies conducted earlier by the research group. The outcomes of the study formed the basics of the use cases that were implemented during the prototype development. From these use cases we gathered further requirements on presentation of information, user interactivity and usability.

Since the implementation of an interactive and usable system requires more than one iteration, we expected requirement changes as we developed the prototype and tested them from users’ perspective.

Later, when we had a working prototype, evaluations with the research group were conducted to refine the requirements.

### 6.1.3. Selecting InfoVis Techniques

The use cases scenarios required that the user be able to interactively narrow down the amount of data to get to the desired information. The operation needed to be quick and should dynamically change any linked views. To support this kind of interactive and coordinated filtering, Parallel Coordinates were suggested to filter down the data while Stacked Graph, List and a Network Map (Choropleth Map) were used to display different views of the same data.

The Parallel Coordinates method has been successfully applied in other scenarios dealing with Multivariate Data. The use of Parallel Coordinates in this scenario was a choice based on the data in use and the requirement of interactively filtering it. The result of the filtering from the PC was the next step in visualizing the Alarms. For this, three techniques namely, the Alarm List, Stacked Graph and Network Map (Choropleth Map) were suggested which were mainly a requirement decision based on how the data was needed to be visualized.

### 6.2. Design and Implementation of Prototype

The prototype development involves using real-time data and a design solution for visualizing it. The design and implementation comprises on the following three major phases:
1. Designing the Prototype
2. Implementation

Having presented the above stages of the prototype development cycle, we cannot overlook the possibility of iterative development in case of requirement changes or less usable design. The design and implementation of the prototype went through several iterative cycles where each new iteration improved on the one preceding it.

6.2.1. Designing the Prototype

The design task not only focuses on designing an interface that represents Multivariate Data, but the visualizations should represent data in more than one form, be linkable/coordinate-able to reflect selection or filtering changes dynamically, and should provide interactive, visual analysis. Moreover, since these visualizations will be part of a bigger prototype, they need to follow intuitive and usable UI Design Patterns.

Using accepted GUI design patterns and principles result in a better user interface for software. Grand’s guideline for GUI design is a good starting point in terms of reusing effective GUI design patterns (Window Per Task, Interaction Style, Explorable Interface, Selection, Direct Manipulation, Ephemeral Feedback, etc.) [25]. While there are specific GUI patterns that can be used either independently or together with each other and as many times as needed, Grand presents the following requirements which leach to their use [25]:

- Use of GUI elements that the users are familiar with.
- GUI components should be consistent with users’ expectations and knowledge.
- The GUI should allow the user to undo the operations.
- The GUI should give warnings about the consequences of operations.
- A GUI must guide the user about its use.
- Provide shortcuts to routine tasks for experiences users.

Tidwell also presents some patterns for interface design[26] that may be helpful in an effective prototype design. While designing the prototype we selected theSortable Table, Liquid Layout, Extras on Demand and other suggested patterns to have better interactivity and intuitiveness.

Interactivity in the prototype is introduced in the different ways a visualization is manipulated. Freitas et al. [4], in their study of usability of InfoVis techniques, define three main classes of interaction, (1) help and orientation mechanisms, (2) browsing and querying, and (3) data reduction functions. We took into consideration these classes when designing the interactivity of the prototype.

6.2.2. Prototype Implementation

The implementation phase is divided in two phases. The first step is low fidelity (Low-Fi) prototypes or mockups which are basically broad ideas and concepts about the interface.
It is always good to start the design with mockups as they are simple, cheap, and quick to produce [32]. They help in reviewing the design at an earlier stage and suggest modifications. Once we have a Low-Fi prototype, we move further to develop a working, high fidelity (Hi-Fi) prototype. This Hi-Fi prototype uses real data and is evaluated in a realistic scenario and is very close to the final product [32].

The Low-Fi prototyping was done using pencil sketches and several computer based sketches were made. The working, Hi-Fi prototype was developed using .Net Framework 3.5, C# language, Windows Presentation Foundation (WPF), Syncfusion Charting and UI Controls[9], and GAV Toolkit for Multiple Linked Views[11].

6.3. Evaluating the Design

The design was evaluated using an experiment that lay down user tasks which follow the interactive querying needs. Several users were asked to carry out the tasks and their progress was observed and timed to measure the effectiveness and efficiency of the prototype and techniques used. The measure of efficiency in the prototype was mainly the amount of time spent in completing a task. A secondary effect of increasing efficiency was on the number of actions a user has to perform to accomplish a task. This effect was hypothesized to cut down the mouse and keyboard operations when using the interface.

To test for the above, a comprehensive test protocol was needed to capture all the qualitative and quantitative data about the experiment. The testing was performed using the methods described by Kuniavsky[27] which include Think Aloud, User Tasks, Observations, Interviews and Questionnaires.

Both qualitative and Likert scale questionnaires were be used to record users’ opinions and responses about the prototype. The evaluation protocol is discussed in detail in Chapter 8.
7. IMPLEMENTATION

The first step towards implementation of the prototype was to develop a Low-Fi prototypes or mockups. This made it easy to review and get feedback, suggestions and comments from the users. The mockups were based on pencil sketches and it was easy to discuss and change them in the beginning without doing much effort.

Figure 7.1 shows a pencil sketch of a Parallel Coordinate plot Stacked Graph. This mockup shows the interaction and connectivity between the user and different elements of the interface. The sketch on the right tries to represent the coordination between the two interfaces.

![Figure 7.1 – Parallel Coordinates and linked views (Left); Interaction between PC and SG and Selection of views within SG (Right)](image)

The result of Filtering and Selection as shown in Figure 7.1 are reflected in Figure 7.2. It is a detailed sketch of Stacked Graph and how data series are plotted on it. After the paper sketches, discussions were done that leads us to next stage of prototype implementation.

![Figure 7.2 – Detailed sketch of Stacked Graph](image)
After the paper based designs, sample software components were developed to test the feasibility of the prototypes. This was the second phase during which initial development of the prototype was done. For this purpose, we used Third Party Charting and InfoVis libraries namely, Syncfusion and GAV. The prototype was based on C#.Net and Windows Presentation Foundation (WPF) [31]. Use of these components enabled us to do rapid prototyping and proof-of-concept while concentrating on our interface and visualization design tasks only. Figure 7.3 shows the first attempt on displaying a time-series Stacked Graph of Alarms using the Syncfusion Library.

![Figure 7.3 - Time-series Stacked Graph of Alarms](image)

Figure 7.4 shows a working prototype in which a stacked graph has been shown. The menu on the left hand side displays options that a user can perform. The suggested features of an InfoVis like Overview, Highlight Zoom, Filter, Details as required and Relationship Management have been implemented in this module. Alarms can be selectively viewed based on Types, Priorities and Status.

![Figure 7.4 – Final implementation of Stacked Graph for displaying Alarms](image)
Parallel Coordinates were mainly implemented to filter the data of Alarms. There were seven different variables in the PC module that can be used to filter with the help of sliders. The blue and red lines in the figure 7.5 represent the Alarms. Moving the sliders up and down on the axes reduces the Alarms in the current and coordinated views.

Figure 7.5 – Final implementation of Parallel Coordinates showing all Alarms in the system

Figure 7.6 – Coordination Control

The coordination feature is shown in Figure 7.6 above. All the views that need to be coordinated must have the option enabled. This enabled the user to coordinate the views of her choice.

The PC can be coordinated with other views like Stacked Graph, Alarm List and Network Map. When coordinated, effects of filtering the data in PC are reflected in other views. A
A snapshot of coordinated view of PC is presented in Figure 7.7. For example, if a user wants to see the list of all the Alarms that occurred during May, 2009, she could move the sliders of the variables of Year and Month in PC module and the result could be seen in the Alarm List as a reduced set of Alarms. The Stacked Graph shows the number of Unacknowledged Alarms at equal intervals in the selected time span and the Network Map shows the regions in which the Alarms occurred, highlighted by different colors depending upon the number of Alarms in the region.

Figure 7.7 – Coordination between Parallel Coordinates, Stack Graph, Alarm List and Network Map
8. EMPIRICAL EVALUATION

To evaluate the use of InfoVis techniques and individual versus Multiple Coordinated Views (MCV) developed in the prototype, an empirical, test-case based user experiment was conducted. Users were asked to perform a set of tasks on the system. These tasks were designed to give a fair opportunity to each visualization technique used namely, Parallel Coordinates and Alarm List.

For this evaluation, Stacked Graph and Network Map were not considered because comparing the two with the Parallel Coordinates and Alarm List was not possible due to the different ways they present data and allow the user to interact. This would have resulted in tasks specific to each interface and not necessarily equal in terms of getting answers. The evaluation would have been biased.

The experiment based on Parallel Coordinates and the Alarm List sought answers to the following questions:

- Which interface do participants prefer for a certain task? Does MCVs facilitate in carrying out the tasks?
- Is there a significant performance gain in using either of the two interfaces?
- What do the users think about the interfaces?

The users were mainly required to do two kinds of tasks, Selection and Filtering for Alarm List and Parallel Coordinates respectively. These tasks could consist of sub-tasks like Sorting for the Alarm List and Reordering in the Parallel Coordinates.

8.1. User Profile

There were a total of 12 participants from within the organization who took part in the evaluation and testing. Of all the participants there were 8 male and 4 female users. They were between 24 and 56 years old. The median age of the participants was 26. The users were familiar with computer use and almost all of them were from Information Technology or Engineering background. All the users were at least Undergraduates while 83% (10 users) had Graduate or higher academic qualification. Some of the participants had background knowledge about the context of application but had not used these interfaces before.

8.2. Observed Parameters

Since the aim of the experiment was to observe users’ performance on the suggested prototype. The factors that affect the performance had to be taken into consideration. The
following parameters were observed during the experiment and while the users did the tasks.

- How much time a user spent in completing a task?
- Did the user come up with the right answers?
- If the users did not get the rights answers in the first attempt, how many attempts and time they took to finish?
- How many discrete actions (Clicks, Keystrokes,Scrolling, Note Taking and Calendar reference each) were involved to complete a task?

To record subjective feedback, the participants were asked to do ‘loud thinking’ during the initial briefing at the beginning of the session and after completion of the tasks when they were interviewed about their experience.

8.3. Design

There were two similar blocks of 12 tasks each (24 in total) ranging from simple to complex on the difficulty scale. The tasks were designed to be performed on both the Alarm List and Parallel Coordinates. These tasks were defined by consulting the experts of the particular system to make sure that similar operations are performed by operators in real settings.

The participants were asked to perform tasks on Alarms Lists alone and on Parallel Coordinates with coordinated Alarm List. To prevent skewed results, the order of the task blocks was balanced between participants, and tasks appeared in random order inside each block. However, for every task in one block, there was an equivalent task in the other. This was done to compare the results side by side for each method for a particular task.

The following variables were recorded during the experiment:

- Subject – For identifying the participant.
- Group – The order in which they did the tasks i.e., Coordinated-Uncoordinated (CU) or Uncoordinated-Coordinated (UC).
- Coordinated – If the views were coordinated or not.
- Answer – Right, Wrong or No Answer.
- PC – Time taken to do the task on Parallel Coordinates.
- AL – Time taken to do the task on Alarm List.
- N – The number of discrete actions performed to complete the task.
- Sequence – The sequence in which the task was performed.
8.4. Setting

The prototype application for this experiment was run on a desktop computer with displays set up like a control room. However, only a minimal number of resources needed for this experiment were used. The computer had large (17 inch), high-resolution (1280x1024), dual screens to show the visualizations side-by-side and was fast enough to instantaneously respond to user’s actions. The experiment apparatus is shown in Figure 8.1.

![Figure 8.1 – The Computer and Screens used to emulate Alarm Monitoring in Control Room](image)

The dataset for Alarms and Events was specific to ABB’s system but was randomly generated to make the experiment easy to conduct. The use of real data however, would not have affected the evaluation because the data used in the evaluations had similar attributes as the real data would have had.

The experiment was video taped to capture user comments and actions while at the same time two observers timed and noted down the participants’ actions while they performed the tasks.
8.5. Pilot Test

A pilot test was conducted in the beginning with a user to check the effectives and completeness of the testing protocol. This identified weaknesses in the briefing methods, tasks and questionnaire. The test design was improved based on these findings before the actual evaluation was conducted.

8.6. Procedure

In the beginning, all participants were briefed about the evaluation and the privacy statement. Then the experiment supervisor delivered a 15-20 minutes introduction to the users using slides and verbal discussion about the problem, context, the interfaces and their use so they feel comfortable with the system. The participants were asked to perform some sample operations to get familiar with the prototype use and “Think Aloud” while they do it.

Each test was conducted separately from all other users and was followed by two observers, in this case, the authors of this report. The observers wrote down the experiment notes, time to perform specific tasks, record the verbal communication and listing to users’ feedback after the tests.

After the completion of the test, the participants were asked to fill out a questionnaire to acquire demographic information, their preferred technique in each task, the difficulties they had with the visualizations, the interface and of course coordinated views.

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 do the tasks as quickly as they could manage but with the aim of getting the right answers.

Figures 8.2 and 8.3 show the two interfaces, A Parallel Coordinates plot and Alarm List from one of the evaluation.
Figure 8.2 – Filtering of Alarms using Parallel Coordinates

Figure 8.3 – Sorting and Selection of Alarms using in Alarm List
8.7. User Tasks

The user testing involved answering a set of tasks or questions using the visualization techniques implemented in the prototype. The answers involved either selecting a subset of the Alarms in the Alarm List using sorting and selection techniques or filtering the dataset using the Parallel Coordinates. Each task could be performed on the Alarm List and Parallel Coordinates independently and the same was done in the experiment to compare the efficiency of one visualization technique over the other. The list of tasks used in the experiment are presented as Appendix – I to this report.

8.8. Questionnaire

Measuring discrete actions and time to complete a task was not sufficient to completely evaluate the prototype. To find out subjective information like user experience, likeness and usability, a questionnaire (see Appendix – II) was used to capture the users’ feedback at the end of the test. Another reason for using such a questionnaire was to compare the users’ perception of the parameters like speed and accuracy that were measured during the observations. This served as a two-way check for the observations from the experiments.
9. RESULTS

There were many facets to the observations from the experiment conducted. However, the most pressing evidence was found in the execution times (Table 9.1) and the number of right and wrong answers per task (Table 9.2). Following is a summary of results for Alarms List and Parallel Coordinates in Coordination with the Alarm List.

Coordinated Parallel Coordinates and Alarm List: Out of the 144 tasks performed by total 12 users, there were wrong answers for 8 instances (5.6% percent of times). While the remaining 136 times (94.4%), users managed to get the right answers. The average execution time for all the tasks was 392.82 seconds (6 minutes 33 seconds). In case of wrong answer, the mean number of reattempts per task were 0.08.

Uncoordinated Alarm List: The users came up with wrong answers for 35 instances (24.3% of the times). While the remaining 109 times (75.7%), the users managed to get the right answers. The average execution time for all the tasks was 1020.32 seconds (17 minutes). The mean number of reattempts per task were 0.82.

<table>
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<th>Task</th>
<th>Coordinated View</th>
<th>Uncoordinated View</th>
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</thead>
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<td>Average</td>
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<td>21.46</td>
</tr>
<tr>
<td>Task 8</td>
<td>9.49</td>
<td>16.89</td>
</tr>
<tr>
<td>Task 9</td>
<td>11.61</td>
<td>28.62</td>
</tr>
<tr>
<td>Task 10</td>
<td>15.50</td>
<td>45.98</td>
</tr>
<tr>
<td>Task 11</td>
<td>29.01</td>
<td>57.17</td>
</tr>
<tr>
<td>Task 12</td>
<td>10.15</td>
<td>65.81</td>
</tr>
<tr>
<td>Total</td>
<td>153.11</td>
<td>392.82</td>
</tr>
</tbody>
</table>

Table 9.1 - Task Execution Time (Seconds)

<table>
<thead>
<tr>
<th>Coordinated View</th>
<th>Uncoordinated View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>Wrong</td>
</tr>
<tr>
<td>136</td>
<td>8</td>
</tr>
</tbody>
</table>

The overall efficiency gain in task execution time between coordinated views and uncoordinated views was 61.5% in the favor of coordinated views. On average, there was a 37.7% decrease in mouse clicks and 97.2% decrease in keystrokes when coordinated views were used. Tables 9.3 and 9.4 show the number of mouse clicks and keystrokes per task respectively.
Table 9.3 - Mouse Clicks Per Task

<table>
<thead>
<tr>
<th>Task</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3.33</td>
<td>5</td>
</tr>
<tr>
<td>Task 2</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>7.33</td>
<td>13</td>
</tr>
<tr>
<td>Task 3</td>
<td>3</td>
<td>7.92</td>
<td>45</td>
<td>3</td>
<td>4.42</td>
<td>13</td>
</tr>
<tr>
<td>Task 4</td>
<td>2</td>
<td>3.25</td>
<td>4</td>
<td>4</td>
<td>5.50</td>
<td>7</td>
</tr>
<tr>
<td>Task 5</td>
<td>4</td>
<td>5.58</td>
<td>7</td>
<td>4</td>
<td>8.42</td>
<td>20</td>
</tr>
<tr>
<td>Task 6</td>
<td>3</td>
<td>5.08</td>
<td>7</td>
<td>3</td>
<td>10.67</td>
<td>25</td>
</tr>
<tr>
<td>Task 7</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>7.67</td>
<td>17</td>
</tr>
<tr>
<td>Task 8</td>
<td>3</td>
<td>3.75</td>
<td>5</td>
<td>3</td>
<td>6.75</td>
<td>21</td>
</tr>
<tr>
<td>Task 9</td>
<td>2</td>
<td>4.33</td>
<td>6</td>
<td>3</td>
<td>8.33</td>
<td>20</td>
</tr>
<tr>
<td>Task 10</td>
<td>3</td>
<td>4.92</td>
<td>10</td>
<td>4</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td>Task 11</td>
<td>4</td>
<td>5.50</td>
<td>9</td>
<td>4</td>
<td>13.92</td>
<td>36</td>
</tr>
<tr>
<td>Task 12</td>
<td>3</td>
<td>5.25</td>
<td>11</td>
<td>3</td>
<td>5.50</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
<td>56.58</td>
<td>120</td>
<td>41</td>
<td>90.83</td>
<td>209</td>
</tr>
</tbody>
</table>

Table 9.4 – Keystrokes Per Task

<table>
<thead>
<tr>
<th>Task</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.92</td>
<td>2</td>
</tr>
<tr>
<td>Task 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.67</td>
<td>6</td>
</tr>
<tr>
<td>Task 3</td>
<td>0</td>
<td>0.08</td>
<td>1</td>
<td>1</td>
<td>2.42</td>
<td>6</td>
</tr>
<tr>
<td>Task 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2.08</td>
<td>4</td>
</tr>
<tr>
<td>Task 5</td>
<td>0</td>
<td>0.25</td>
<td>3</td>
<td>1</td>
<td>3.33</td>
<td>7</td>
</tr>
<tr>
<td>Task 6</td>
<td>0</td>
<td>0.17</td>
<td>2</td>
<td>1</td>
<td>4.25</td>
<td>11</td>
</tr>
<tr>
<td>Task 7</td>
<td>0</td>
<td>0.08</td>
<td>1</td>
<td>1</td>
<td>3.58</td>
<td>7</td>
</tr>
<tr>
<td>Task 8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2.83</td>
<td>11</td>
</tr>
<tr>
<td>Task 9</td>
<td>0</td>
<td>0.17</td>
<td>2</td>
<td>1</td>
<td>3.67</td>
<td>11</td>
</tr>
<tr>
<td>Task 10</td>
<td>0</td>
<td>0.25</td>
<td>2</td>
<td>2</td>
<td>4.25</td>
<td>17</td>
</tr>
<tr>
<td>Task 11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>6.08</td>
<td>21</td>
</tr>
<tr>
<td>Task 12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.83</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>11</td>
<td>36.92</td>
<td>108</td>
</tr>
</tbody>
</table>

Among the tasks, there were three levels of difficulty: Easy, Moderate and Difficult depending upon the number of variables involved. Coordinated Parallel Coordinates performed better in most of the cases. The easiest task took 14.26 seconds on average, a moderate task took 33.13 seconds and the most difficult task took 57.17 seconds on average to complete. Figures 9.1, 9.2 and 9.3 show box plots of task execution time by all the users for easy, moderate and difficult tasks respectively.
Figure 9.1- Execution time for easy tasks

Figure 9.1 shows the variation in task execution times for each of the easy level tasks. There are large variations for Uncoordinated tasks while for all but one of the Coordinated tasks, there is a considerably small difference between the users’ performance. The discrepancy in Task 2 for the coordinated run can be attributed to unfamiliarity with the interface as this task was presented in the beginning of the evaluation.

Figure 9.2- Execution time for moderate tasks
The same can be seen for moderate level tasks in Figure 9.2. All the coordinated tasks except for Tasks 4 and 12 have very low execution times as compared their uncoordinated runs. Both of the Tasks 4 and 12 were unique in a way and made the users to think for some time. Task 4 was the first moderate level task a user encountered. Hence the longer execution time as compared to other moderate level tasks. Task 12 on the other hand was posed as an analytical statement which was difficult to understand by most of the participants.

There was a remarkable difference in execution times for the difficult tasks. Users performed clearly better when Coordinated views were used as compared to uncoordinated ones in terms of minimum, maximum and average execution times. The results are depicted in Figure 9.3 below.

![Comparison of Execution Time for Difficult Tasks](image)

Figure 9.3- Execution time for a difficult tasks

Figure 9.4 shows the comparison between Coordinated and Uncoordinated tasks with respect to their mean execution times. The performance of coordinated views is clearly, far better the uncoordinated view.
The results so far show that the use of Parallel Coordinates and Coordinated Views is very efficient as compared to Uncoordinated Views. However, the experiment design has to be verified. The tasks were grouped and presented in random order among the participants in the following two groups:

1. Group UC - Coordinated tasks first and Uncoordinated tasks later
2. Group CU - Uncoordinated tasks first and Coordinated tasks later

Figure 9.5 shows that the use of such groups did not have considerable effect on the users’ performance. In spite of the order (UC or CU) in which the tasks were presented, the average execution times per task deviate only slightly for Coordinated views. However, it is noteworthy that the CU group performed comparatively better on Uncoordinated views for moderate and difficult tasks.
Figure 9.5 - Average execution time per task

Questionnaires and user interviews conducted at the end of the experiment produced some statements about the interfaces and provided user ratings on their different aspects. Figure 9.6 presents a box plot of key attributes of the Alarm List interface that we wanted to evaluate where 1 is the least rating and 7 is the highest. A similar box plot for Coordinated Parallel Coordinates and Alarm List is shown in Figure 9.7. Use of Parallel Coordinates and Coordination of the two interfaces resulted in an overall better performance.

Figure 9.6 - Box plot based on user rating of Alarm List’s attributes
The second part of the evaluations also captured subjective user responses about the interfaces. During Think Aloud and Interviews about both the interfaces, the key statements that were recorded are presented below.

**Coordinated Parallel Coordinates and Alarm List:**
- Fast and easy to operate and intuitive.
- Less cognitive load, no need to think about order of sorting.
- Gives a good overview of the dataset.
- Unfamiliar concept but easy to learn.
- Preferred way of filtering alarms.

**Uncoordinated Alarm List:**
- Similar to existing Windows interfaces.
- Sequential sorting is a strength when an overview or sequenced groups are needed.
- Gives a detailed information and a feel of number of alarms.
- Useful for smaller datasets.
- Too much information at once.
- Takes long time to get to desired results especially if number of parameters are more.
- Backtracking from error states is not possible, user must restart the task.
- Less sense of history or feedback to the user.
10. DISCUSSION

Results presented in the previous chapter show that Parallel Coordinates and Multiple Coordinated Views give better performance to the users as compared to the Alarm List both in terms of execution time, correct answers to tasks and other usability attributes like efficiency, effectiveness, speed, memorability, learnability, accuracy, understandability etc. Although done in the specific area of Control Room systems, this study provides strong results that Parallel Coordinates and Coordinated Views perform better for Multivariate Visualizations.

There were exceptions in some cases though. The performance of coordinated views was far behind that of Alarm List when the results were compared by per user - per task basis. These exceptions can be attributed to a number of variables. One reason was the understanding of the tasks. A few users did not grasp certain analytical tasks however these tasks were of moderate difficulty. In another incident, a user preferred using the Alarm List even in coordinated view because of her long term use of such an interface. Such factors affected the users’ performance poorly in the coordinated views. One implementation related factor affecting the performance was the delay in the sliders of PC. Had this been eliminated, the performance of PC and MCVs would have been better.

It is important to point out here that even with the initial training, most of the participants in the experiment took time to get trained on using the interfaces. Participants pointed out that only after a few tasks (3 to 6) in the coordinated view, were they comfortable with the interface. This was more (6 to 8 tasks) for the uncoordinated view. This could be a reason for irregularities in the performance of some of the users. Even with the occasional difficulty in using the coordinated views by few of the users, we see a marked difference in the manner users rate the interfaces. The box plots in Figures 9.6 and 9.7 show the clear advantage of using the PC and MCVs although some tasks took lesser time to complete on an uncoordinated view.

Earlier studies conducted by Godinho et al.[15] concluded that the use of PC does not harm the performance of user tasks and helps improve filtering and visualization. These results corresponds to the finding in this report. However, unlike the results in Godinho’s study [15] about “General Users” and “Computer Professionals”, the performance of the participants was consistent regardless of their computer expertise. Siirtola’s work[22] was very close to the evaluation done in this research. We can argue that besides validating Siirtola’s work, this study provides more concrete results on the use of PC and MCVs.

During the interviews after the evaluations, several design enhancements were pointed out by the participants. These are listed below:

- Implement “Excel Like” filtering of records in Alarm List.
- Implement “Grouping” by attributes in the Alarm List.
- Implement “Instant” filtering in Parallel Coordinates if one of the categorical values is clicked.
• Implement “Snapping” of sliders in Parallel Coordinates if there are discrete values on the Axes.
• The feedback for high and low values of sliders in Parallel Coordinates is more prominent if they are displayed besides the sliders as they move.

Though the results from the empirical evaluation are positively in favor of MCV, it would be beneficial to use different evaluation techniques to validate this study. Conducting the evaluations in the real environment and with more number of participants who are actual operators having proper domain knowledge would yield better results. However, the problem with such usability evaluations is their lack of discrete measurements and a concrete result. Evaluation becomes very difficult when we try to test subjective responses of users on interface design features which themselves are relative and abstract in nature. Evaluating the effect of coordination with Stacked Graphs and Network Map could be the next step for this study.
11. CONCLUSION

The research work addressed the challenges of presenting large amount of Multivariate Data in Control Room environment. We selected and implemented some InfoVis techniques to visualize data in power grid control systems. Task based user evaluations were conducted to measure the effectiveness and efficiency of the prototype and InfoVis techniques implemented. Overall, the use of Parallel Coordinates and Multiple Coordinated Views with Stacked Graph, Network and the especially the Alarm List proved beneficial for visualizing and filtering the Alarms.

The contributions of this research are two fold i.e., both to the academia and the industry. For the academia, this research has produced stronger results as compared to earlier studies that were related to Parallel Coordinated and Multiple Coordinated Views. For the industry, the suggested solution is one of the first of its kind and is most likely to be implemented in the existing applications in use.

11.1. Answers to Research Questions

1. How can Multivariate Data in Control Rooms be represented efficiently using alternative techniques?

The question was answered by analyzing different InfoVis techniques. User requirements for a control room environment were gathered and use cases scenarios were developed for implementation of a prototype.

The requirements from the analysis and design phase resulted in the prototype development where the selected InfoVis techniques were implemented. The four techniques selected and implemented in the prototype were Parallel Coordinates, List (Alarm List), Stacked Graph and Choropleth Map (Network Map). Coordinated Views were implemented to interactively visualize the result of filtering.

2. Does the use of filtering by Parallel Coordinates over Lists improve trend analysis of Alarms and Events?

The quantitative result of the experiment results show that PC (in coordination with Alarm and Event List) has several benefits over Lists. Almost all of the participants felt discomfort and spent more time (as compared to PC) while performing a task by using List. The use of PC made the filtering procedure fast, easy and smooth. We noticed that the PC also helped the user to find the correct answers for the tasks. The evaluation results imply that while using PC, out of the 144 tasks performed by the users, there were wrong answers 5.6% percent of the times. But on the other hand, the participants came up with wrong answers 24.3% of the times while performing the same tasks by using Alarm List only.
3. Does the use of Multiple Coordinated Views facilitate the filtering tasks for Parallel Coordinates?

Coordinating Alarm List and Parallel Coordinates plot was evaluated against the use of Alarm List alone. The experiment result explains that PC has several benefits over the Alarm List. The observations show that the filtering operation in list is complicated and require a lot of thinking. It becomes more complex to filter the data when there are three or more variables involved. On the other hand, users felt more comfortable while performing the same task by using PC in coordination with Alarm List. The most important of results is the considerable reduction in the number of clicks and keystrokes per task, decreased the cognitive load and above all, the minimized execution time when PC was used in coordination with the Alarm List. It was also noticeable that the users really like the notion of coordination and made use of it.

To conclude, use of Parallel Coordinates and Multiple Coordinated Views enhanced the efficiency and effectiveness of the visualizations and user tasks for filtering Alarms and Events.
12. FUTURE WORK

Future work in terms of the validity of this research could be in more than one direction. Firstly, part of the prototype was not evaluated in this study. The next step could be to evaluate the efficiency and effectiveness of coordination with the Stacked Graph and Network Map. Coordination between more than two InfoVis techniques at a time should also be tested. However, a more functional test plan is needed to evaluate such functions.

Several design suggestions that were identified during the evaluations are presented in the discussion chapter. Implementing those suggestions could possibly improve the efficiency of both the techniques evaluated in this study. A reevaluation of these approaches can produce stronger and even less biased results when the existing interfaces are improved.

The suggested interfaces can be improved to a great extent by implementing different techniques of querying. One way is to add a search function on Alarm List for filtering the data. This way, a user could enter desired variable (dates, source etc.) and then compare the results with Parallel Coordinates. The order of sorting the data in Alarm List should also be somehow improved as it can be seen from the experiment results that user forgot the sorting pattern and hence took a long time to complete a task.

This study could have revealed more accurate results if the participants in the study had proper domain knowledge. Since the experiments were conducted with users who were not real operators, it is debatable whether employing real operators of the system would be beneficial for the overall research. Since the idea was to see new user reacts to the interfaces when using them for the first time, it would be interesting to observe the work practice of actual operators given the same scenarios. Also, the experiment could be conducted with more realistic data and actual control room environment.

Further validation of this study can be done by conducting a similar evaluation in real Control Room environment. It would be better if the actual operators (who work in a control rooms) evaluated this prototype. As they work in a real environment, they could have provided more valuable feedback.
REFERENCES


APPENDICES

Appendix – I: User Tasks

<table>
<thead>
<tr>
<th>Task No.</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highlight all the Alarms that occurred from March 2009 to May 2009.</td>
</tr>
<tr>
<td>2</td>
<td>Highlight all the Alarms that occurred during May 2009 and have Priority 5 or higher.</td>
</tr>
<tr>
<td>Last March saw a considerable number of Alarms in the System. You need to find out if there were any critical Alarms during that period.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Highlight all the Alarms that occurred for the month of March 2009 with maximum Priority.</td>
</tr>
<tr>
<td>4</td>
<td>Highlight all the Alarms that occurred for the month of April 2009 with Priority 5 or higher and are Unacknowledged.</td>
</tr>
<tr>
<td>Sometimes even low priority Alarms may have significance and should be checked if needed.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Highlight Alarms of type “Spontaneous Breaker Trip” having Priority 2.</td>
</tr>
<tr>
<td>6</td>
<td>Highlight Alarms that are Unacknowledged, are of type “Controls” and have minimum Priority.</td>
</tr>
<tr>
<td>7</td>
<td>Highlight all the Alarms for the month of March 2009 with type “Protection” having the highest Priority.</td>
</tr>
<tr>
<td>8</td>
<td>Highlight all the type “Control” Alarms for the month of March 2009 that are Unacknowledged, with Priority 3 or higher.</td>
</tr>
<tr>
<td>Alarms that have not been acted upon remain in Unacknowledged state and may pose a problem if not resolved.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Which Stations (Source) have currently the most number of high Priority, Unacknowledged Alarms?</td>
</tr>
<tr>
<td>10</td>
<td>Which Stations (Source) have currently the most number of type “Protection” Alarms and are Unacknowledged?</td>
</tr>
<tr>
<td>11</td>
<td>In April 2009 which Station (Source) got minimum “Control” Alarms with Priority 3 or higher?</td>
</tr>
<tr>
<td>There may be pikes in the system activity after a weekend or national holiday.</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Analyze the Alarms that occurred between last Monday and Tuesday and give a relative measure of their quantity.</td>
</tr>
</tbody>
</table>
Appendix – II: Post-User Tasks Questionnaire

Name: ____________________________________ Age: ______ Gender: ___________

Education:
High School, Undergraduate, Graduate, Postgraduate, Doctorate, Other:_________

How do you rate your IT skills?
Experienced, Adequate, Basic, Other:_________

How would you rate your familiarity about Information Visualization or Human Computer Interaction (HCI) related concepts?
Experienced, Adequate, Basic, Other:_________

What are the strengths and weaknesses in the Alarm List and Parallel Coordinates tools?

<table>
<thead>
<tr>
<th></th>
<th>Parallel Coordinates</th>
<th>Alarm List</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weaknesses</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on your perception and experience, rank the features and use of Parallel Coordinates.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Rank (1-7, 7 being best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (How quickly were you able to perform the tasks?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Intuitiveness (Did the interface expressed its intended use?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Accuracy (How accurate were the results?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Understandability (To what degree the functions of the system are clear?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Interactivity (To what degree the system responds to user actions?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Pattern Identification</td>
<td>1 2 3 4 5 6 7</td>
</tr>
</tbody>
</table>
Based on you perception and experience, rank the features and use of Alarm List.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Rank (1-7, 7 being best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (How quickly were you able to perform the tasks?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Intuitiveness (Did the interface expressed its intended use?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Accuracy (How accurate were the results?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Understandability (To what degree the functions of the system are clear?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Interactivity (To what degree the system responds to user actions?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Pattern Identification (Were the patterns in data evident in the visualization?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Learnability (How easy was it to learn the use of the system?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Memorability (To what degree the functions present in the system are remember-able after first use?)</td>
<td>1 2 3 4 5 6 7</td>
</tr>
</tbody>
</table>

How is the coordination between the two tools helpful in identifying the patterns or filtering data?

How would you rate the coordination feature?

<table>
<thead>
<tr>
<th>Rank (1-7, 7 being best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
</tr>
</tbody>
</table>

Other comments: