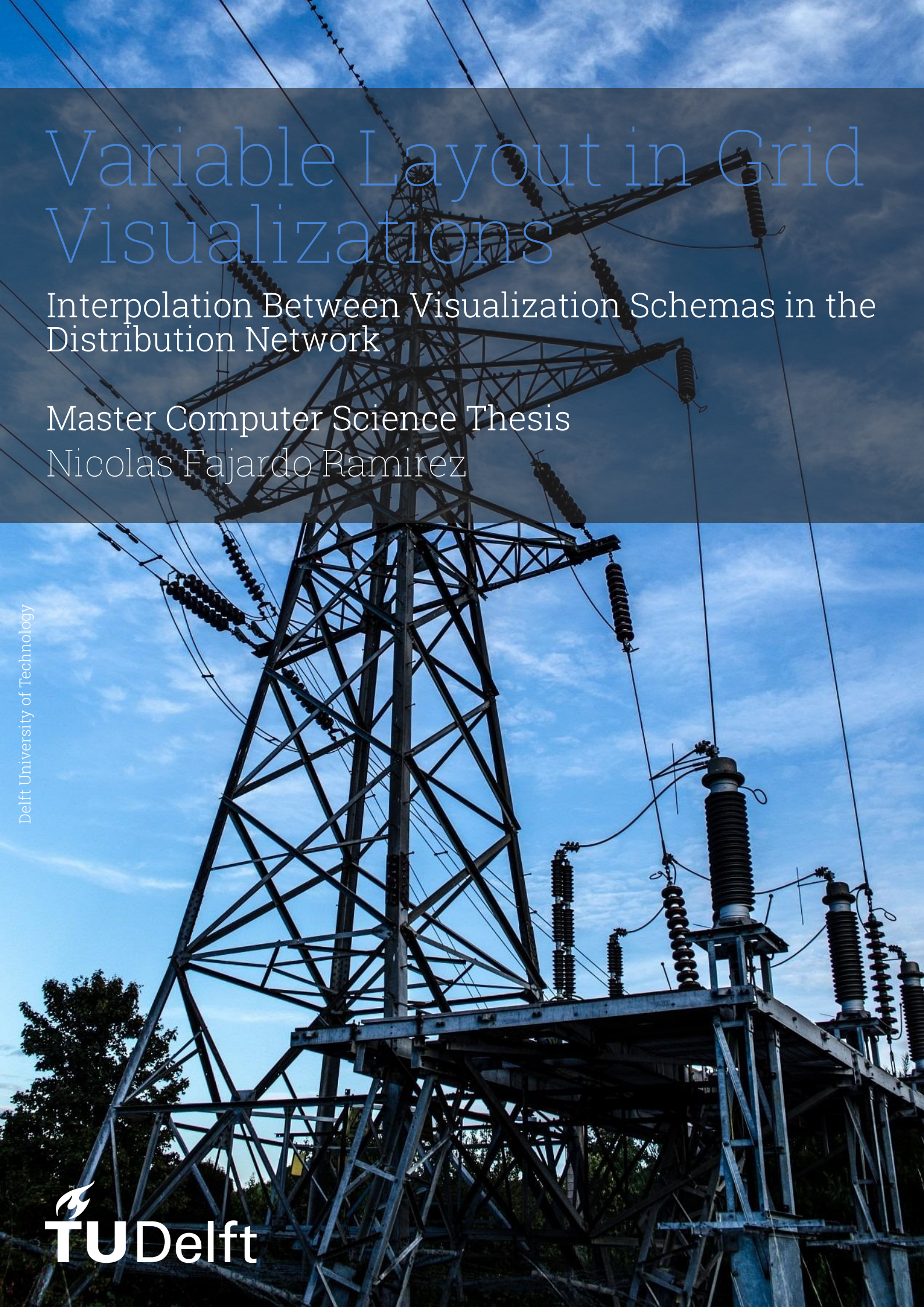


Variable Layout in Grid Visualizations

Interpolation Between Visualization Schemas in the Distribution Network

Master Computer Science Thesis

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Variable Layout in Grid Visualizations

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Abstract

The power grid is the infrastructure that allows electricity to be delivered from its generation point to the end users in consumers, businesses and services. Failures in this infrastructure can cause severe economic damage and create dangerous situations. Strong situational awareness can help grid operators in having a better understanding and reaction capabilities to both prevent these failures and accelerate recovery processes. One requirement for this is the need for a clear perception of the environment. This is usually done by the use of different applications and dashboards to monitor the state of the grid. The focus of this research is to create a visualization tool that allows the grid operators to see two different representations of the power grid, a geographical and a topological one in the same view. A slider-based visualization was proposed in order to give the grid operators the capacity to change between these views in a controlled and smooth manner in order to avoid loss of focus and reduce the cognitive load that occur when this information is presented in different views. A user study was performed to assess the effectiveness of this visuaization compared to two different visualizations inspired in other common methods to visualize both representations: geographical and topological side by side, and on different applications. The participants were all students and young professionals divided into two groups: those that had experience in similar domains and those that did not. The results showed no significant difference in accuracy when using the slider visualization compared to the other two methods, but users were slower using it. When assessing each user group separately, the experienced user group showed no significant differences in speed among the three methods, whereas the inexperienced user group was significantly slower only with the slider visualization when comparing it with the side-by-side visualization. Also, it was found that when using the slider, users tended to spend more time in the intermediate views between the geographical and topological view. This trend was particularly strong in the experienced users group. Finally, the slider-based visualization was also perceived as being more enjoyable and interesting by the users compared to the other two methods. In general, it was found that a slider might be a useful method to merge these two views; however, more work is needed to both improve its performance and assess its utility in more realistic scenarios.

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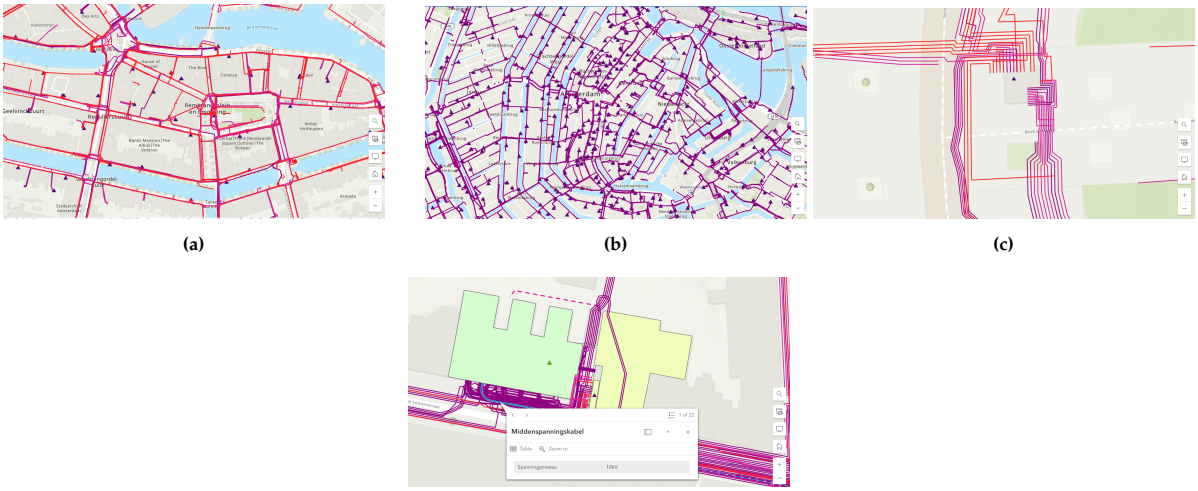
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Introduction

Electricity is one of the most important commodities in modern society, as it powers homes, businesses, and services such as hospitals, public transport, and telecommunications. The power grid is the infrastructure that encompasses its generation in power plants, its delivery through power lines, and its use by consumers [40]. This system connects power plants to consumers around cities and countries, resulting in a vast and complex network. One example of its size is the Dutch power grid, as the part of the grid operated by just one of the Distribution Network Operators (DSO), Liander [23], has more than 96,000 kilometers of power lines and 5.9 million connections [4]. Given the dependence society has on this commodity, failure in this infrastructure can have big consequences like traffic lights stopping working, failure in heating and cooling systems, electrrified rail systems coming to a standstill, among many others [41]. An example of this is the case of the Iberian peninsula total blackout of April 2025, which resulted in mass chaos [11]. One factor that has significantly contributed to these kind of events is the insufficient situational awareness by grid operators [34]. Situational awareness can be defined by three aspects [10]: significant perception of environment cues, comprehending their significance, and projecting forward in time to determine how these will affect future states.

In the case of the power grid, perception can prove to be challenging due to the large amount of data that operators have to keep track of, which often comes from different sources. Afzal et al. [1] studied the cognitive load on operators during training and real-time operation with the aim to determine the causes of this load and provide recommendations on how to reduce it. One particular recommendation stated is to combine key applications or sources that provide complementary information, as the operators had to go back and forth between them to get the information they needed. One possibility to consider is to combine two common grid representation methods in one view: geographical and topological. These two representations provide different information of the power grid, that both help to give the complete picture.

The geographical representation displays the grid over a map using the real-world positions of the components. This is useful for monitoring purposes during emergencies, as operators can use it to monitor critical infrastructure and weather or traffic events, to efficiently deploy teams and forecast damage [12]. Furthermore, geographical representations can be useful for planning new connections [26], getting a quick overview, or just communicate information to non-technical stakeholders. One major drawback of these representations is that, by preserving the real-world coordinates of the components, understanding the topology or focus on individual components can be difficult as depending on the case, there can be a lot of components in a small area. Figure 1.1 shows this phenomenon in Amsterdam's power grid.

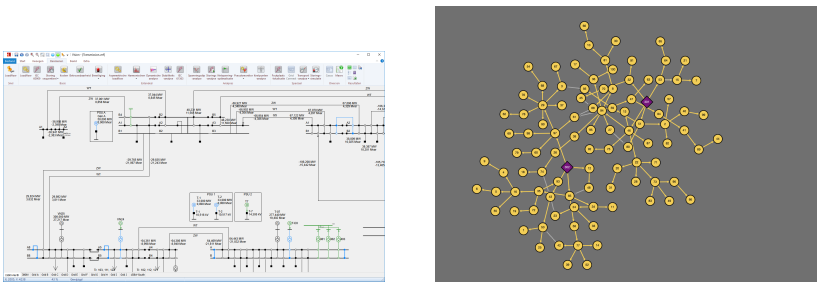


(a) **(b)** **(c)**

(d)

Figure 1.1: Geographical View of the power grid in Amsterdam [24] [22]

Topological representations, on the other hand, focus more on clearly displaying the connections between elements. These representations can make it easier to visualize the impact on the structure of the grid when some components fail, at the cost of losing all geospatial information. One common method of doing this is to use Single Line Diagrams (SLD). These are technical diagrams that use specific notation and rules to represent each component and its connections. Figure 1.2a shows an example of a SLD on the Vision Network Analysis program [37]. Another way to have a topological representation is via node-link diagrams, which can have different layout styles. Figure 1.2b shows an example of a node-link diagram generated by the Power Grid Model DS visualizer [45] using a force-directed layout.



(a) Single Line Diagram example from Vision Network Analysis [37]

(b) Force-Directed Layout example from Power Grid Model DS [45]

Figure 1.2: Example of single line diagrams

Since both representations of the grid are needed to get a complete view of the grid, operators might need to use them at the same time; however, applications can sometimes offer just one, or both in different tabs, making the operators go back and forth between them. This is the case at Alliander [2], a Dutch energy company that owns the network operator Liander, who proposed this project to mix both representations in a single view, to avoid a back and forth change between different tabs or applications. Thus, this project aims to develop a visualization that integrates both a geographical and a topological representation of the grid in a single view. This way, users can get all information they need without needing to look away to different views or application, following the recommendation stated by Afzal et al. [1] to reduce the cognitive load of operators while they do they work.

As designing effective data visualization can be a complex task, it is useful to separate this process into parts. One approach to this is to use the four nested levels of visualization design framework created by Tamara Munzner [27]. This method separates the process of developing a visualization into four

cascading levels that encompass the entire process and validates each step to ensure its effectiveness. Given the objective of improving the operators' efficiency with the use of this visualization, the focus for the validation is to reduce the time it takes them to get the information they need, while retaining accuracy.

Apart from the efficiency and accuracy, another metric that is important to validate is the user experience of using the visualization. This is true since a bad user experience might prevent efficient visualizations from being used as much due to user preference. This will be evaluated using the User Experience Questionnaire (UEQ) [20], which is an empirical approach to measure user experience in a quick and simple manner.

1.1. Research Question(s)

The main research question to be tackled by this project is:

- RQ1: How does a controlled transitioning visualization between a geographical and a topological representation of the grid compared to traditional approaches in terms of the speed of grid operation tasks and user experience?

In addition to this, some secondary research questions are of interest to the project:

- RQ2: How can we effectively communicate information retrieved from the grid data in a transitioning visualization between a geographical and a topological representation?
- RQ3: Is a complete change of context between a geographical and a topological view of a grid necessary for grid operation tasks?

1.2. Contributions

The contributions in this research are as follows:

- Development of a visualization tool that allows users to transition between a geographical and a topological representation.
- Design and execution of the validation procedures for evaluating this visualization in comparison to two methods of visualization for a geographical and a topological representation (RQ2).
- An evaluation of said validation showed that there was no significant difference between the accuracy of users when using the proposed tool and two other common methods; also, there was no difference between the task speed for experienced users (RQ1).
- An evaluation of the user experience showed that it was more interesting and enjoyable to use compared to other methods (RQ1).
- It was observed that there are cases where an intermediate visualization without a full context change can be enough to get the required information (RQ3).

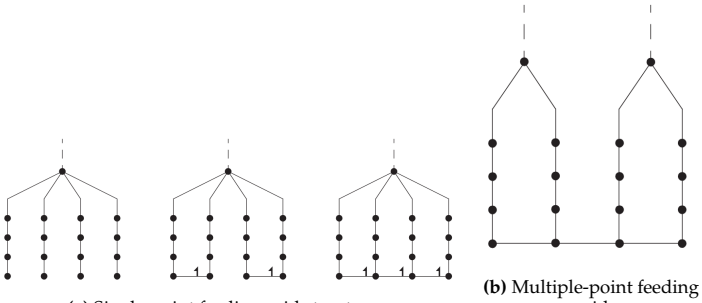
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Background

This section contains the relevant backgorund information for the research. Section 2.1 introduces the power grid and section 2.2 exposes previous work on its visualization. Section 2.3 introduces the power grid model library, which will be extended with the visualization tool. Section 2.4 explains the visualization design framework used to design and validate the tool, while section 2.5 explains the validation method that will be used to evaluate the user's perception in the tool.

2.1. Power Grid

The power grid is the infrastructure that allows electric power to be generated, transported, and utilized [40]. *Generation* of electric power mainly occurs in power plants that produce power by drawing energy from different sources [42]: thermal plants burn coal, oil, and gas, nuclear plants take the energy released from the fission process of uranium atoms, and renewable plants use naturally renewable resources for energy, like solar, wind, geothermal, or hydroelectric. Other sources of generation include households and businesses that have their own solar panels to generate the power they need and sell the excess back to the grid [19]. *Transport* of power basically consists of receiving the power from the power plants' substations at High Voltages, and then transporting it towards the end consumer while passing through more substations that gradually reduce the voltage until it reaches the final supply station that serves the power directly to the consumers [43]. Each of these final supply stations generally serves between 50 and 100 clients. In general, grid structures can be distinguished into parts with single-point feeding, which receive electric power from a single point, and multiple-point feeding, which receive electric power from multiple points. Figure 2.1a shows the three possible structures for a single-point feeding part of the grid, while Figure 2.1b shows a multiple-point feeder grid structure. Transport of power consists of two steps: *transmission* and *distribution*. Transmission refers to the process of sending the power from the power plants to the different population hubs over large distances using High Voltage (HV) power lines, generally more than 100kV. Distribution is the process of distributing the power within those population hubs using Low (LV) and Medium (LV) Voltage power lines (less than 100kV). *Utilization* is the use of the electric power by the final consumer: households, businesses, or utilities, among others [44].



(a) Single-point feeding grid structures

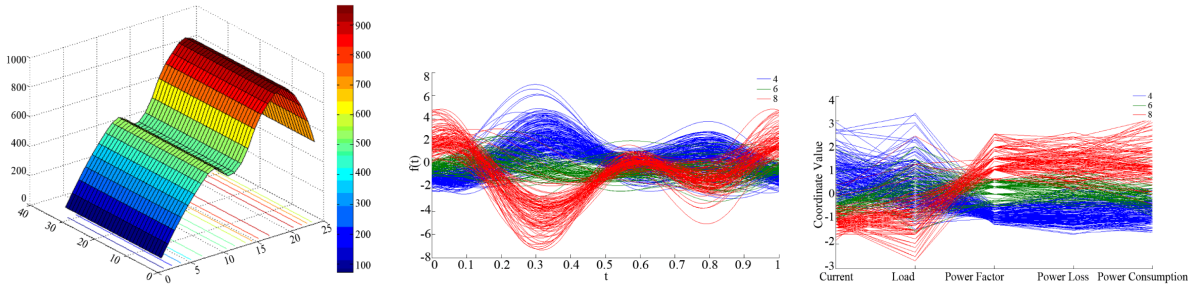
(b) Multiple-point feeding grid

Figure 2.1: Single-point feeder and multiple-point feeder grid structures [43]

In this research, the main focus is the portion of the grid that takes care of the distribution step: the distribution grid. This focus is because of the high number of components that it has. An example of this is the grid operated by Alliander [2], a Distribution System Operator in the Netherlands, that by 2025 had over 5.9 million consumer connections and 90,000km of power lines [3]. Even though the impact of failures in this part of the grid might not be as serious as failures in the transmission grid (failures in the transmission grid have the potential to cause massive blackouts, while failures in the distribution grid have more localized effects), there are a lot more components here that can fail, and it's a bigger challenge to monitor it.

2.2. Visualization in the Power Grid

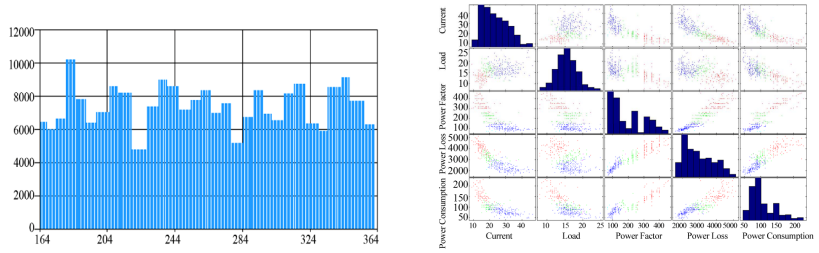
There are many common methods to visualize information from the power grid, tailored for different purposes. On one hand, there are some traditional methods like using time series bar charts or 3D surface contours for low-dimensional data, or diagrams suited for more complex data like scatter diagrams, parallel coordinates, or Andrew curves [33] [14] [39]. These diagrams are useful as they provide information on both an overview of the grid data, like the average consumption per hour and day of the week/month, or real-time measurements, like current or voltage in specific points of the grid, that can be added to dashboards for monitoring purposes. Figure 2.2 shows examples of some of the traditional diagrams mentioned, while Figure 2.3 shows an example of a dashboard used for monitoring.



(a) 3D surface with contour

(b) Andrew's curve

(c) Parallel Coordinates



(d) Bar Chart

(e) Scatter Diagram

Figure 2.2: Traditional charts/diagrams [33]

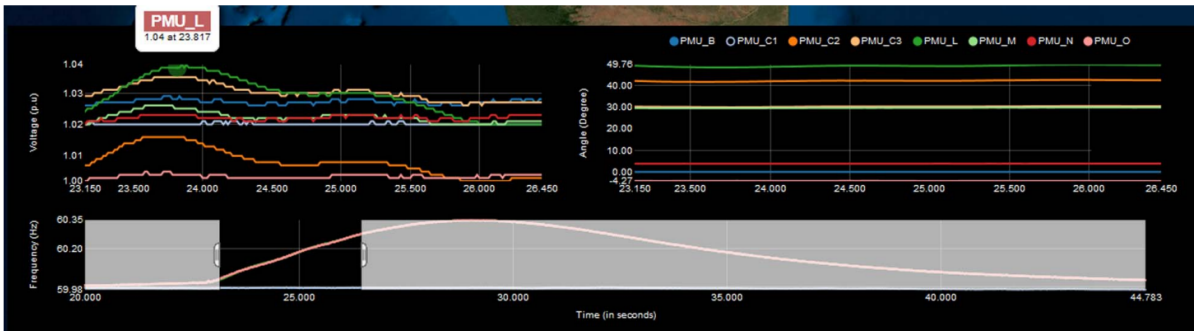


Figure 2.3: Dashboard example [5]

2.2.1. Geographical Information Systems

Another common visualization tool is the use of Geographical Information Systems(GIS) [33]. These systems show the grid components over a map, in the actual coordinates where they are installed. These diagrams help in giving the operators the complete picture of the grid by providing geographical context, which can help in monitoring, decision-making, and pattern detection, among others [13]. Several Software tools can provide these types of visualization. Proprietary software like Power Factory [9] or ArcGIS [13] both provide GIS visualization for the grid and displaying SLD views. These solutions, however, display these views in a separate manner, so users might lose focus when alternating between them. There are also open-source tools like Open Street Map [35], an online map visualizer with data of power grid infrastructure, bicycle road maps, among others. This solution, however, lacks a topological view of the grid infrastructure.

2.2.2. Force Directed Placement

Force directed placement is a method that models attractive and repulsive forces to generate layouts for graphs [15]. The original method follows two principles: vertices connected by an edge should be close to each other, and vertices should not be drawn close to each other. To do so, two formulas are defined to model the behavior of nodes and edges of the graph. First, an attractive force on nodes that share an edge $F_a = \frac{d^2}{k}$. Second, a repulsive force for each pair of nodes $F_r = -\frac{k^2}{d}$. Where d is the distance between the nodes, and k is a constant, usually defined by $k = C\sqrt{\frac{Size\ of\ the\ drawing\ area}{Number\ of\ nodes}}$ for a constant C that needs to be experimentally found. Then, starting on an initial layout, several iterations of this force are applied until an equilibrium position is reached. There has been extensive research on improving this method. Some notable work in this area includes: strengthening forces to converge nodes closer to each other before equilibrium so larger graphs can be drawn [7], defining a short-range force based on the Student's t-distribution that yields better neighborhood preservation [55], or a multilevel three-stepped approach consisting of coarsening the graph, refining the layout and interpolating the result to improve the efficiency when drawing large graphs [49].

Some authors have even applied these techniques for drawing topological representations of the power grid. For example, Birchfield and Overbye [6], who use force-directed inspired techniques to model the attractive force F_a between the nodes of the graph and their geographical position to find an appropriate spacing for the substations (nodes), and then uses a Delaunay Triangulation-based approach to route the lines to avoid overlapping of components. Another notable approach is Green Grid [51]. Green Grid is a visualization system based on a multilevel weighted force-directed placement algorithm that uses properties of the power grid as weights to base the forces on. This results in layouts that keep a certain level of geographic congruency while allowing for clear insights into high-density regions. A usability study was also performed, in which it was confirmed that this layout generally offers "equal or improved performance over the geographical layout in terms of accuracy, time to completion, and user satisfaction".

In this research, the student's t-distribution inspired force [55] will be used for layout generation. This will be explained further in Section 3.3.

2.2.3. Single Line Diagrams

Single Line Diagrams (SLD) for the power grid are designed with the purpose of displaying its topology as clearly as possible. There has been extensive research on the automatic creation of these diagrams. Some notable ones are: methods based on the trunk-and-branches model that draw it by first identifying the largest path from the substation to the furthest connection and then branching out which results in a diagram that is easy to read [48], the use of an evolutionary approach to optimize the layout under some constraints [56] [25] [21], and the use of a two-stepped process of manually reducing line crossings and later optimizing the layout by solving a MILP model [50], along with an efficiency improvement upon this method [54].

For the creation of the SLD view of the grid, the trunk-and-branches model-based approach [48] will be implemented. This will be explained further in Section 3.3.

2.2.4. Transitioning Visualizations

An attempt to do a transitioning visualization between a geographical placement of components and a SLD was made by Hoang et al. [18]. In their research, a prototype that quickly transforms the view between a geographical representation and a Single Line Diagram of the electrical system of a university campus was developed. The transformation is triggered by pressing a button that starts an animation of the view transforming into the other one by disassembling its components, transforming them into the glyphs of the other visualization, and then reassembling them in their new layout. The system got a positive reception during its validation tests, and users highlighted some benefits it could have. Particularly for education or training purposes, since it helps make the connection between the diagram and the real system, and helps building management personnel who do not have much electrical experience in diagnosing problems in the system before calling an expert. It is important to note that the results obtained from the validation test were entirely qualitative, and no efficiency assessment was made. These results, however, are of use for this research as they provide some precedent on possible use cases of these kinds of visualization.

Another thing to note is that the method chosen for the transformation might not be the most ideal for grid operation task purposes, as the animations that do the transformation move too fast, making it difficult to follow individual components.

2.3. Power Grid Model

Power Grid Model (PGM) is an open-source library used for steady-state distribution power system analysis [52] [53]. This library offers both symmetric and asymmetric calculations for power flow, state estimation, and short circuit calculations. The library also has an extension project called Power Grid Model DS (PGSM-DS) that extends its capabilities to include a modeling and simulation interface that can be used for building data science software applications related to the Power Grid model projects [45]. Notably, this extension project also includes a visualization capability for visualizing the modeled grid. Since this extension project has tools for modeling grids and has visualization capabilities for them, it is going to be used as a starting point for building the visualization. In other words, the development of the tool will be an extension of this open-source library.

2.4. Visualization Design Framework

The four levels of validation is a set of guidelines defined by Tamara Munzner in her book 'Visualization Analysis and Design' [27] for visualization design studies. This consists of a nested model of four levels of design tasks to be followed to tackle visualization design problems, and a validation process in each level. Figure **??** shows the four levels, along with the validation processes, and a detailed explanation of each level is as follows:

- **Domain Situation**: This step consists of understanding the situation of the target users and defining their need in domain-specific terms. This will be done in Section 3.1.
- **Data and Task Abstraction**: This step consists of taking the domain specific needs identified in the previous step, and abstracting them into generic tasks and data, used to select the idioms in the next step. This will be done in Section 3.2.

- **Visual Encoding and Interaction Idiom**: In this step the idioms are selected. Idioms can refer to either visual encoding (what users see) or interaction (how users change what they see). This will be done in Section 3.3. The validation process will be done in Section 3.5.
- **Algorithm**: This step refers to the implementation of the algorithm that produces the selected idioms using the data. This will be done in Section 3.4.

In addition to this framework, Munzner also describes two different angles of attack to visualization design: problem-driven and technique-driven. Problem-driven design involves the design of a solution to a problem of a real-world user, which must follow all four levels of the framework. Technique-driven design, alternatively, focuses more on the idea of creating new idioms or algorithms, in which only the last, or last two, levels are followed.

2.5. User Experience Questionnaire

The User Experience Questionnaire (UEQ) is a standardized questionnaire designed to measure the user experience on products [20]. This questionnaire was developed starting on 80 questions, which were later reduced to twenty-six questions divided into six scales: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. Though originally designed in German, it is now available in 30 languages and different tools have been created to help in the standardized analysis of the responses [17]. Several additions to this questionnaire have been developed over the years. These include: a benchmark to interpret evaluations of products [46], a method for calculating KPIs based on questions evaluating the perceived importance of each scale [16], and a short version of the questionnaire consisting of 8 out of the 26 questions [47].

Since one of the validation methods for the visual encoding and interaction idiom level of the visualization design framework is to conduct a laboratory study, the UEQ is of great use to us to assess the user experience of the design in the visualization. In particular, the UEQ short version will be used since the efficiency and user experience of the developed tool will be evaluated against two other visualizations. Since the participants will need to answer a questionnaire for the three different visualizations, this short version is of particular use, as reducing the number of questions reduces their mental fatigue, and the evaluation will be more accurate. In addition, the benchmark will also be of use for the study as a metric to see how this visualization compares to other products.

3

Method

This section contains the design, implementation, and validation process for the visualization tool built. As mentioned in the previous section, this methodology is the result of following Munzner's model for visualization design [27]. This framework will be followed up until the idiom validation process, as the main focus is not deploying a tool but rather to evaluate the idioms developed.

This methodology starts with the Domain Situation, where the process of understanding what visualization tools are used for in power system analysis is done in order to identify possible situation blocks that will be translated into use cases for the validation process. Then, the Data abstraction will follow, a section in which pre-processing decisions will be explained and an abstraction of the resulting datasets will be provided. Then, the Task abstraction, where the different situation blocks will be abstracted into domain-agnostic tasks to aid in the final design of the visualization. Next is the Visual Encoding and Interaction Idioms, where the design of the tool will be thoroughly explained, and the Algorithm and Implementation section will provide a detailed explanation on the implementation procedures. Finally, this chapter ends with an explanation of the design of the validation tests for the visualization tool designed.

3.1. Domain Situation

To get an understanding of the domain, a set of ($N_{DS} = 5$) PhD student members of the Intelligent Electrical Power Grids research group at TU Delft were interviewed. This set was previously screened to ensure that the participants had experience in power systems analysis and had some experience using visualization tools in this field. They were first contacted during a presentation at a colloquium where the idea of the proposed tool that merges both a geographical and topological representation of the power grid in a single view was presented. Then, those interested were prompted to fill out an interest form to be later contacted to schedule the interview. In general, the participantes mentioned that the use they gave to visualization tools in their tasks was very limited:

- Interviewees 1 and 5 mentioned that they used grid visualization functionality of systems like Power Factory [9] and Power World Simulator [38] only for setting up grid models by manually connecting and disconnecting components using the user interface, and setting some of its parameters.
- Interviewee 4 mostly used Panda Power [36] to display test grids and ensure proper distribution of missing data for testing machine learning modelsand PyPSA [8] for estimating the leveled cost of grid expansion scenarios.
- Interviewees 2, 3, and 5 mostly used visualization tools like Panda Power, PGM, or self-made libraries to get rough visualizations of the grid, and a quick way to visually identify components such as overloaded lines in the grid.
- Interviewee 3 also used Panda Power to display the grid for teaching purposes.

After this, the interviewees were asked about possible uses they would give to this project's visualization

tool. Interviewees 2, 4, and 5 mentioned that it would be useful for planning purposes and testing different scenarios. Interviewees 2 and 5 said that it would be useful to identify clusters. Interviewee 3 said that it can be used to highlight important components. Interviewee 4 also mentioned that it could be useful to check distances between nodes. Finally, Interviewees 1, 4, and 5 mentioned that this type of visualization can be useful for the distribution grid, as reading it can prove to be difficult due to its size. Note that these last findings all suffer from courtesy bias, as the interviewees did know that these possible use cases were important for the research, and though they thought about useful scenarios, they might not be actually convinced that they exist. In total, a list of six general tasks was identified:

- **S1**: Test different network configurations in simulations. This is based on interviewees 1 and 5, who manually build the grid models using the UI to later test on simulation.
- **S2**: Identify important components. Important components are defined as nodes or edges in the grid that can have a considerable impact on the grid. Examples of this are overloaded lines (lines that are receiving more current than they can handle), feeder nodes of specific portions of the grid (nodes are the sole feeders of electricity of portions of the grid), among others. This is based on some of the comments made by Interviewee 3
- **S3**: Get an overview of the grid. Not necessarily looking for anything in particular. It can be both driven by curiosity on seeing its structure or might also be interested in finding patterns. Based on some of the use that interviewees 2 and 5 give to the libraries.
- **S4**: Identify clusters of high consumption nodes. Based on some of the comments made by users 2 and 5. The situation does not necessarily apply to identifying the specific components but can also extend to identifying which areas of the map have these clusters of high consumption.
- **S5**: Evaluate the costs of new connections. Based on the experience of interviewee 4.
- **S6**: Check the distance between nodes. Based on the comments of interviewee 4

These tasks will be abstracted into domain-agnostic tasks in section 3.2.2.

3.2. Data and Task Abstraction

3.2.1. Data Abstraction

This section will focus on following Munzner's framework [27] to abstract the data, so it will be easier to identify appropriate idioms to build the visualization tool. The data used in this project comes from two sources:

- Data from the Liander grid [32]. This data consists of a geometric dataset consisting of around 100 thousand Point items (substations, medium voltage installations, and low voltage distribution boxes), and 1 million Line items (low, medium, and high voltage cables). The point items are defined with the geospatial coordinates of the point, while the line items are defined as line strings with the list of geospatial coordinates that make up the path of the cables, as these are not straight lines.
- Data model of the Grid element of the PGM DS library after a power flow calculation [45] [53]. This is a network dataset with attributes on both nodes and links. The links represent the cables of the grid, while the nodes can represent sources (which provide power to the grid) and loads (that consume power). The node attributes depend on the type of node; however, only attributes of the load nodes are of interest, as the source node has no attributes of significance after the power flow calculation. The reason for choosing the power flow calculation outputs as data is because this allows for having realistic data that can be used to test the visualization in the validation process.

These two datasets were merged into a single one by sampling radial grids of several sizes (tens or hundreds of nodes) from the Liander dataset, with each one containing exactly one source node that acts as the power source of the whole grid. This results in a tree dataset according to the framework [28]. These radial grids of only hundreds of nodes were sampled since these could be used to generate simple test cases that the users in the validation step could use to test the tool. Position fields were also added to each component: a geospatial coordinate for the nodes and a list of geospatial coordinates for the links. This abstraction can be found on Table 3.1 where for each attribute, its component and

abstraction are shown. This abstraction will be of use for selecting the idioms that will be used to build the visualization tool in section 3.3.

Attribute	Component	Abstraction
ID	Nodes and Links	Ordered-Ordinal-Sequential
Path	Links	List of Geospatial Positions
Rated Current	Links	Ordered-Quantitative-Sequential
From Node	Links	Ordered-Ordinal-Sequential
To Node	Links	Ordered-Ordinal-Sequential
Loading Percentage	Links	Ordered-Quantitative-Sequential
Current	Links	Ordered-Quantitative-Sequential
Position	Nodes	Geospatial Position
Active Power	Nodes	Ordered-Quantitative-Diverging
Reactive Power	Nodes	Ordered-Quantitative-Diverging
Voltage	Nodes	Ordered-Quantitative-Sequential
Voltage Angle	Nodes	Ordered-Quantitative-Cyclic
Active Power Injection	Nodes	Ordered-Quantitative-Diverging
Reactive Power Injection	Nodes	Ordered-Quantitative-Diverging

Table 3.1: Attribute Abstraction

3.2.2. Task Abstraction

This section will focus on following Munzner's framework [29] to abstract the different situation blocks identified in the domain situation step into domain-agnostic tasks. By doing this, it will be easier to identify appropriate idioms to build the visualization tool. This abstraction process will be found below:

- **Test different network configurations in simulations (S1)**: this situation block entails building different network configurations via UI to later test on script-based simulations in order to assess its behavior. Therefore, this will be abstracted as ***T1*** - *Derive Topology*
- **Identify important components (S2)**: this situation block entails identifying important components in the grid. As explained in Section 3.1, important components can have several definitions, depending on the task at hand. Therefore, this will be abstracted as ***T2*** - *Discover Features*, where the features can refer to the output attributes of power flow calculation, the position of the component, or features related to the connections.
- **Get an overview of the grid (S3)**: In this situation, the user might want to just look around the grid, hoping to find something, so ***T3*** - *Overview Topology or attributes* are a nice fit.
- **Identify clusters of high consumption nodes (S4)**: In this case, users are interested in finding clusters of nodes that have a high load after the power flow calculation. Therefore, a ***T4*** - *Discover group of nodes with high attribute values* is appropriate, as the user is interested in finding locations where nodes in the grid tend to have a larger than normal consumption.
- **Evaluate the costs of new connections (S5)**: In this case, the user is interested in estimating the cost of a new connection to the grid. With the data in hand this cost can be related to the length of the new cable and the characteristics of its path: whether there are more cables passing through (meaning that there is infrastructure that can be utilized) or geographic features in the path (like waterways, buildings, etc.). Therefore, this can be abstracted as ***T5*** - *Identify Cost Causes*.
- **Check the distance between nodes (S6)**: In this case, the user just wants to identify the distance between nodes in the grid. As the user is presumed to know the nodes in question and where they are, they just need to look at that place and make the estimation. Therefore, this can be abstracted as ***T6*** - *Lookup Distances between known nodes*.

Some of these abstracted tasks will be used to complement the base design of the visualization in the following section. Particularly, the focus will be on **T2**, **T3** and **T6**, as these were later traduced into tasks for the users to do in the validation step. This will be explained in Section 3.5.

3.3. Visual Encoding and Interaction Idioms

As mentioned in Section 1, the focus of the study is to develop a tool that allows to have a geographical and topological representation of the grid in the same view. As there are several methods of creating a topological representation of the grid, it is also of interest to evaluate more than one option, as some might be more suitable to complement with a geographical representation on the same view. Thus, the following three views will be created:

- **Geographical view**: a view where the components of the grid are shown to match their real spatial positions. This is generated based on the geometric data obtained from the Liander dataset [32]. Furthermore, a map background will be added to this view, to give geospatial context to the users. This view supports task **T6**, as showing the real-world position of the components allows users to get a sense of the distance between them.
- **Traditional SLD view**: This is a view where the grid is arranged in a structured way that minimizes line crossings between the links of the network and improves readability. This view was created by deriving the positions of the layout inspired by the trunk-and-branches model presented in [48]. This method was selected, as it is suitable to represent the radial structure of the tree dataset, using the source as root. Section 3.4 will further explain the implementation of this method.
- **Force-Directed view**: This is a view based on a force-directed placement layout for the power grid as a SLD to improve readability of the topology without completely losing spatial information. This was achieved by implementing a Force-Directed Placement simulation following the model presented in [55]. This method was selected as it improved readability, while preserving local neighborhoods compared to methods presented in [6] and [7]. Section 3.4 will further explain the implementation of this method.

Since the data related to these is tree (network) data, the most common encoding is to do a node-link diagram for each view, where nodes are drawn as points and links as line marks [30]. To generate this data, more position fields were added to the nodes and links of the tree, to represent the position and paths of the components in each of the topological views. The use of the node-link diagram supports task **T3**, as users can get an overview of the topology by looking around these diagrams. It also supports task **T2**, as users can get a sense of the components deemed important due to topology.

As for the method for changing between the views, a slider component was chosen. This idea was introduced in early talks with the Alliander representative who proposed the project. During the design process, other alternatives were considered. Particularly: a transforming the views between the two representations using a button, inspired on the work in [18], and using only one representation that mixes both representations in one, similar to the force-directed view. The button idea was rejected as the users lack control over the transformation, making it hard to follow. The mixed-view representation was rejected as it would be equivalent to only having a topological view with some geographic information, which was not the intended goal of the study. The slider method, on the other hand, gives the user complete control over the transition between views: they control the speed, can stop or go back at any time, and is quite intuitive to understand how it works. As for the method to translate the components between the views, a linear interpolation of their positions was chosen. This is because it is a simple and direct method to do these movements, while also easy to understand as components follow the same trajectory between the views. As for the arrangement of the views in the slider, the geographical view was placed on the middle position, the force-directed on the left, and the traditional SLD on the right. This design choice was made in order to give users the liberty to choose which of the views they would rather use for doing their tasks.

Figure 3.1 shows the final design of the visualization. Below is the list of the rest of the design choices made and their justification that supports the cases of task **T2** for components deemed important for their attributes, and task **T3** for the attribute overview:

- As there were two types of nodes of interest in the data model, sources and loads, and only one single-source node existed per sample grid, it was decided to use different glyphs to represent each of these. Small circles represent the load nodes, while a bigger purple diamond represents the substation (node of type source). The size difference was made to properly display the different types of data since there are many more nodes of type load than nodes of type source, so it was

easier to distinguish the latter. The decision of a purple color is not based on anything in particular except a visual difference with the colors used in the color scale that will be explained in the next points. Lines were simply represented as lines in all three views.

- It was decided to encode the different quantitative attributes (Table 3.1) of the components in the network using color as a visual channel. Depending on the quantitative type, an appropriate color scale was selected. A saturation scale was used for the line attributes and the sequential node attributes: red for the lines and blue for the nodes to show a clear contrast. For the diverging and cyclic attributes, as these were only present in the nodes, the node colorscale was updated to be diverging with white in the middle. In it, the right side (positive values) uses the same blue color scale as the sequential scale for the nodes, and a heat-based colorscale was used for the left side (negative values), to show a clear contrast with the sequential scale of the lines. The decision of using color as a channel was done as it was the most effective channel according to Munzner's effectiveness ranking for the magnitude channels in ordered attributes [31] for this case. Using position, length, depth or tilt would not work, as the geographical representation requires specific positions and line paths to represent the components. And area was also discarded as the high ammount of data points would make the visualization too dense and prone to occlussion. Therefore, these color scales were the most effective option for this case, as they help encode the magnitude of the property in a clear way that does not cause occlussions or spatial incongruencies.
- Since nodes and lines have different attributes of interest to be represented, two interaction idioms were added. First of all, some drop-down menus were added to change the current property being encoded with the color. And users can change it by just clicking the drop-down to open it and selecting the new one. This process will also update the color scale of the corresponding property by updating the values on both ends of the scale. This was selected as it is a simple and intuitive way to select a property of interest between a discrete set of options.
- An interaction was added to enable users select any component of the grid and see a more detailed description of its attributes. When users click on a component it gets "selected", and its attributes are displayed in a text box on the top right of the corner of the screen, to avoid visual clutter inside the main area of interest. Users also get visual feedback to let them know which component they have currently selected: for the nodes, including the substation, the border thickness is increased, and for the lines, their stroke width is increased. With this interaction, users are able to select different components to get the attributes of components of interest without generating a lot of visual noise.



Figure 3.1: Main design of the visualization

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3.4. Algorithm and Implementation

This section will focus on explaining the three main algorithms used for the visualization design: the layout algorithms for the two different SLD views and the algorithm for the interpolation to transition

between the views.

It is relevant to mention that in the design process, a list of metrics to evaluate the readability different grid topology was taken from Wang's approach to automatic topology generation [50] in order to select the most effective for each case. However, in the case of the evaluated algorithms for the force-directed implementation, only the t-force based showed promising results, as other algorithms such as [7] and [6] presented either irregular movements that ended up in a disorganized view, or showed barely any significant change in the layout independent on the starting parameters. Wang's implementation itself was deemed too inefficient, as moderate sized grids took too long to create.

3.4.1. Traditional SLD

The calculation of this traditional SLD layout was made via an adaptation of the method implemented by [48]. This method is based on the trunk-and-branches model, which, in summary takes the longest path from the root to a leaf, given that single-point feeder radial nodes are used and marks it as the trunk. Then it starts placing the rest of the leaves as branches that emerging from the trunk. The original method assumes that nodes are not just points in space but can contain more information (like internal wiring of the component); therefore, it uses some procedures to optimize the layout: expand the space to avoid overlapping, contract this space to reduce the size of the diagram, and carry out device wiring to avoid overlaps. The local stretching in the original method can considerably extend the size of the diagram, which is not the case for this project as the nodes are just simple points in space. For this reason, in this method only local stretching is implemented, as it does not make the diagram too large and allows for suitable spacing between components to make it readable. Figure 3.2 shows a close-up on the results of the implementation of the algorithm in the grid from Figure 3.1.

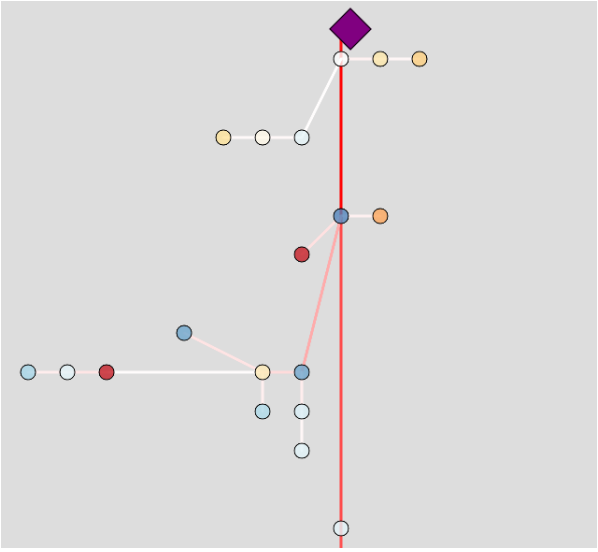


Figure 3.2: SLD View

3.4.2. Force-Directed

The force-directed layout is calculated using the method proposed in [55]. This method consists of defining a new force function, called a t-force, based on the t distribution. This type of force was chosen as it has an upper bound for short distances, avoiding massive repulsive forces that generally occur when two nodes are really close. And it also does a smooth reduction to a force of zero as the distance decreases. The result is a force-directed layout for the graphs that preserves local neighborhoods in a way that improves readability. This is the main reason to choose this approach for the force-directed representation, as other methods that were explored to create a topology representation with some spatial congruency did not show appropriate representations, or were too inefficient to consider for the size of the grids that are being used, as explained earlier in this section.

The t-force is defined as $f(d) = \frac{d}{(1+d^2)^{\phi}}$ for the distance d between a pair of nodes and a constant ϕ.

Figure 3.3a shows the t-force under different ϕ values, which shows the behavior explained earlier. The attractive and repulsive forces of the force-directed placement are then defined as:

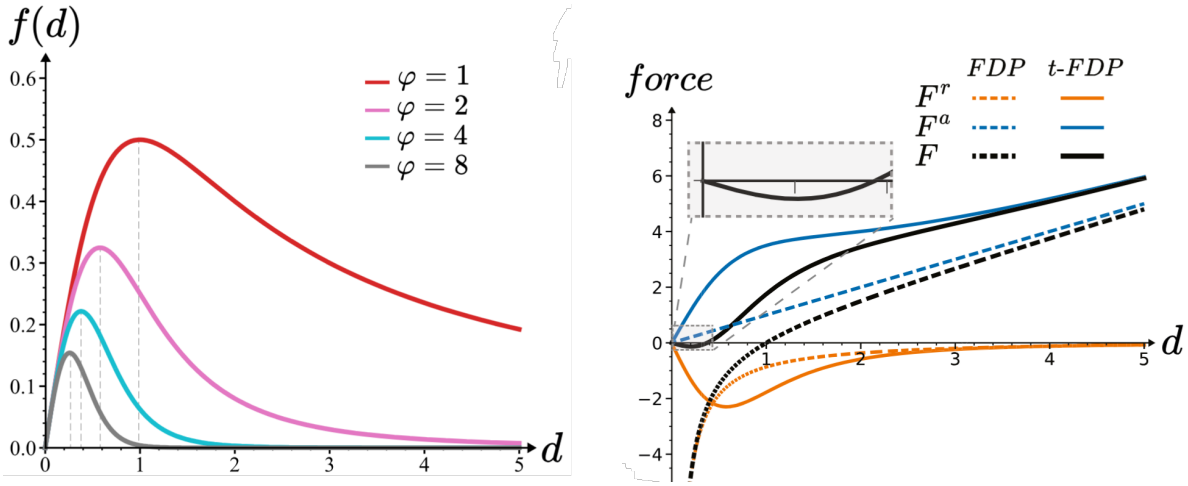
$$F^r(i,j) = -\frac{\|\mathbf{x_i} - \mathbf{x_j}\|}{(1 + \|\mathbf{x_i} - \mathbf{x_j}\|)^\gamma} \frac{\mathbf{x_i} - \mathbf{x_j}}{\|\mathbf{x_i} - \mathbf{x_j}\|}, i \neq j$$

$$F^a(i,j) = \left(\|\mathbf{x_i} - \mathbf{x_j}\| + \frac{\beta \|\mathbf{x_i} - \mathbf{x_j}\|}{1 + \|\mathbf{x_i} - \mathbf{x_j}\|^2} \right) \frac{\mathbf{x_i} - \mathbf{x_j}}{\|\mathbf{x_i} - \mathbf{x_j}\|}, i \leftrightarrow j$$

Where the repulsive force F^r occurs between all pairs of nodes, and the attractive force F^a occurs only between nodes that share an edge. The combined force on node i is then defined as:

$$F(i) = \sum_{j \neq i} F^r(i,j) + \alpha \sum_{j \leftrightarrow i} F^a(i,j)$$

The behavior of these forces can be seen in Figure 3.3b. In particular, the use of the t-force causes repulsive force in short distances to not become too strong. Parameter γ specifies the extent of the magnitude of the repulsive force, with larger values resulting in shorter range forces. Parameters α and β specify the weight of the long-range and short-range attractive force. In general, a configuration of $\alpha = 0.1$, $\beta = 8$ and $\gamma = 2$ is recommended; however, during the implementation, values of $\alpha = 0.01$, $\beta = 8$ and $\gamma = 1$ were found to be effective for the grids.



(a) **(b)**

Figure 3.3: (a) T-force under different ϕ values. (b) Attractive, Repulsive, and total force [55]

Figure 3.4 shows a comparison between the same grid in Figure 3.1 and the corresponding grid after implementing this algorithm.



(a) GIS view of the grid

(b) FDGSLD view of the grid [55]

Figure 3.4: Comparison between the GIS and FDSLD views

3.4.3. Component transition

The chosen transition method to switch between the different views was a simple linear interpolation of each component's position. This was chosen as it is a direct method to move the components between the geographical representation and the two topological representations. This is also intuitive and predictable, as the trajectories followed by the nodes are straight lines, making it easier for users to follow the transition. In addition, this method is computaionally efficient, as it has a linear complexity of $O(n)$, with n being the sum of the total number of nodes and total number of vertices in all of the line strings that represent the power lines. This was appropriate for the test, as the grids used for the validation lab studies were of sizes of about a couple of hundred so current machines can easily handle this transition in real time with minimal latency. No other methods were considered, as the focus of the research is not to build the most efficient transition method between layouts, but rather to show a clear method to transition between them. Thus, for the reasons tated above, linear interpolation was found to be sufficient.

3.5. Validation process

This section focuses on explaining the design of the validation tests to assess the efficiency and perception of the visualization tool. Before proceeding with the test design, it is important to mention that, as part of the objective of assessing the efficiency of the developed tool, it was necessary to have some way of comparing this efficiency with some common methods. For this reason, a couple of other interactions were implemented in a test application that follows the same guidelines as the main visualization but uses different ways of displaying the single line and geographic information. Figure 3.5 shows these two ways. Figure 3.5a is inspired by commercial solutions that allow users to see both a geographical and traditional SLD representation and interact with either of them on any side and see changes reflected on both locations. To emulate this, some interaction was added, mainly the fact that when selecting a component in either of the views, the corresponding component in the other view will also be highlighted. On the other hand, Figure 3.5b is created to show the case when users need to use different applications for the process of visualizing both representations. To emulate this behavior, users have to click on a button to change between the views. When making this change, the system stores where the user was and at what zoom level before changing the views, so when they come back, they get back to where they were. Similar to the previous visualization, users can select any component in either of the views, and the corresponding one will be highlighted. This was made to aid users in keeping some focus on the components, as the constant context change can be quite difficult to manage. Note that these additional visualizations do not include the Force-directed view. This design choice is mainly to emulate the fact that most of these applications show the traditional SLD only.



(a) Side by Side visualization

(b) Tab visualization

Figure 3.5: Comparison visualization

3.5.1. Initial test design

This initial test consisted of a set of three distinct tasks for users to do. These tasks were created based on the domain situation analysis, specifically, they are inspired by the following situation blocks:

- **S2** Identify Important Components.
- **S3** Get an overview of the Grid.
- **S6** Check the Distance Between Nodes.

These tasks were specifically designed to force the users to use both representations (geographic and topological) at the same time.

The first task consisted of highlighting an area in the grid that encompasses some nodes and having the user find the closest feeder node to all of them (**S2/T2**). Figure 3.6 shows an example of this task. In this case, the area has nodes **N**, **K**, and **J** inside. Node **L** feeds to both nodes **N** and **K**, but not to node **J**. Node **I**, on the other hand, feeds node **J** and node **L**, which makes it feed nodes **N** and **K** indirectly, making it the answer.

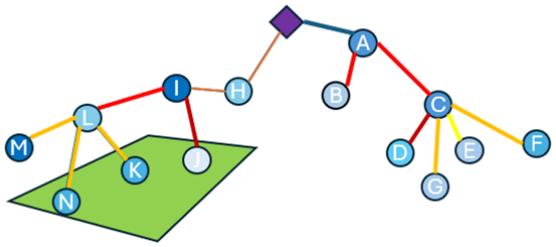


Figure 3.6: First task of the initial test

The second task consisted of finding a new connection path from a portion of the grid that got disconnected because of the failure of a line. To do so, participants had to consider two things. First, by connecting the disconnected grid to the main grid, the path from the connection point in the grid up until the substation will have an extra load of current, which is indicated in that task information, and they must avoid having any lines reach overload condition (having more current passing through them than the rated current of the component). Also, users must find the shortest possible new connection for this purpose (**S6/T6**). For these tasks, users were meant to be aided by the selection interaction to see the actual information in the grid, and the encoding of the properties via the color to visually identify possible routes that had enough capacity to handle the connection. Figure 3.7 shows an example of this task. In this case, the disconnected grid is represented by all of the nodes in black, and the failure occurred in the line connecting nodes C and A. In this case, the best possible route is to connect nodes J and D. This is because connecting F and D, which is the closest route, results in overload because the line between nodes A and B is already overloaded.

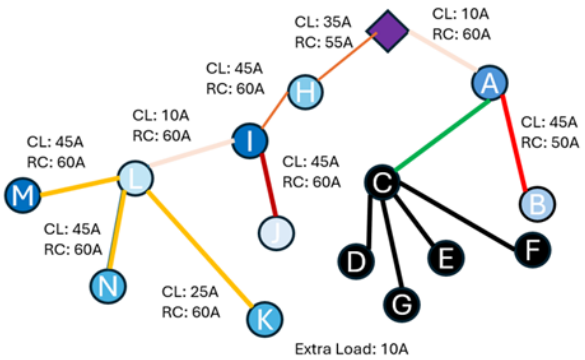


Figure 3.7: Second task of the initial test

The final task consisted of having a select number of nodes in the grid be highlighted and marked as failing nodes, and defining that all of the descendant nodes, that is, nodes that are by these failing nodes, are also failing (**S3/T6**). The users were also given some highlighted areas of the map, and they had

to find which of these had the highest number of failing nodes. Figure 3.8 shows an example of this, where nodes C and L are failing. And there are three zones. Zone 0 that has notes G, E, and F, Zone 2 that has Node B, and Zone 1 that has notes N, K, and J. In this case, the solution is zone 0, because it has three failing nodes. As nodes G, E, and F are all descendants of node C.

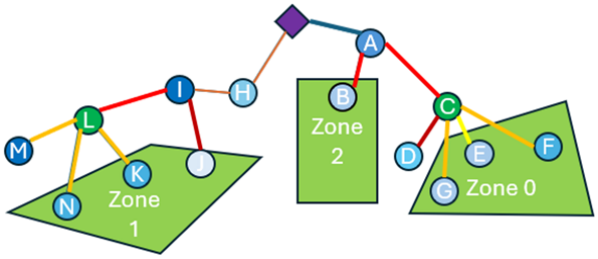


Figure 3.8: Third task of the initial test

The general test procedure that was designed is as follows.

- First users were handed a short tutorial in which they got explanations on some important concepts on the grid, the different interactions, and the instructions on the tasks.
- Then users had an opportunity to do a repetition on each of the tasks using each of the visualizations in really small grids of less than 20 elements, using the same grid for all of the repetitions of the same task before starting the actual test.
- Then the test started. During the test, users had to do two repetitions of each task using each of the visualizations on bigger sample grids of about one hundred to two hundred nodes, for a total of eighteen tasks. For each task, there were six sample grids, one per repetition of the task, that each user had to do. To avoid biases, the users were divided into three groups. Each group received the tasks in a different order. Also, the users had to complete all repetitions of the same task before proceeding to the next one.
- To reduce the bias due to novelty, learning curve, or fatigue, the repetitions of the same task were completely randomized. So, the visualization style for each sample grid was randomized, ensuring that it was two repetitions per visualization, and then the order in which the users received these sample grids was also randomized.
- After the test, users were given a small questionnaire that collected some information regarding their work area and experience with both power grid and visualization tools in general, to assess the experience level of the user. This questionnaire is also the short version of the user experience questionnaire (UEQSs), to assess the perception that the users had of the visualizations. They had to fill one UEQs per visualization schema (slider, side, tab). This questionnaire also asked them to rank their preference in each of the schemas.
- After this questionnaire, a short semi-structured interview followed, where users were asked about the main pain points or the benefits that they felt with each of the visualizations.

This test procedure was not executed at large scale, mainly because there was a failure in predicting the time it actually takes. So, after some initial tests with a sample size of three users, it was clear that it was impossible to continue doing the test like this, as each of the users took about two or more hours to complete the test. For this reason, a revised version of the test design was made to simplify it and make it possible to do a larger-scale study to collect enough data to draw proper conclusions.

3.5.2. Final test design

The test procedure for this final test design is as follows:

- Users read a short tutorial on the test that includes some important concepts, information about the visualization, and the task objective.
- Users then had the opportunity to ask questions to clarify any misunderstandings before starting the test.

- The test itself consisted of doing two repetitions of a single task using the three visualizations. So, in total, a user had to do six tasks, which is a third of the number of repetitions from the first test.
- Similar to the initial test, the users were divided into three groups. Each group alternates the order in which they received the visualization. In this case, order A presented the visualizations in the order first slider, then the side by side, and then the tabs; order B presented the visualizations to the users in the order side, tab, and then slider. And finally, order C presented them with the visualizations in the order tab, slider, and side. Also, the tasks were randomly assigned to each visualization style for each user.
- Users were then asked to fill out a questionnaire, followed by the semi-structured interview same as the initial test.
- A short extension of the test was made for wheeling users that consisted of doing four more repetitions of the same visualization with the slider interaction but using bigger grids. The slider only alternated between the geographical view and one of the two SLD alternatives, so they performed two repetitions per SLD alternative. This was made in order to assess differences between the use of each of the two visualizations, and this was followed again by a short questionnaire and interview. In this case, the users were divided into two groups, and they were presented with the visualizations in alternating order. The group defined which visualization the user was presented first.

It is relevant to mention that the extension of the test was added after roughly two thirds of the user tests were done, as during the testing process it was clear that users were not observed to use much the FDSLD side of the slider. This extension was added to ensure the collection of data on the use of these two representations.

The task selected is based on the first task from the previous section (**S2/T2**). This is because that task had the highest effect on making the users use both of the views of the grid. There was a small addition to the task. Users had to find not the closest feeder in terms of topology, but rather the closest feeder in terms of geographical closeness (**S6/T6**). Figure 3.9 shows an example of this task. In this case, node H would be the answer, as it not only fits all of the nodes inside the area, but it is also the closest geographically.

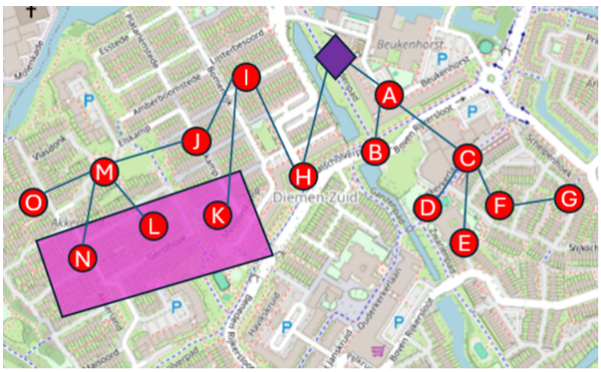


Figure 3.9: Task used for the final test.

In addition to shortening the number of tasks that the user had to do, other changes were made to the procedure. Specifically, the interface of the task was simplified. This is mainly because to solve this task, users no longer need any information regarding the attributes of the components. Figure 3.10 shows this design. In general, all of the nodes were now of a single color, and the interactions were reduced: Users no longer had access to the dropdown menus or the color bars for that matter, since they did not need to really view any of the node or line properties. Also, when selecting a node, they no longer saw the text box with the information. However, they still can select the notes in order to mark them as the answer, and as a way to not lose focus on which part of the grids they are looking at.



Figure 3.10: Design of the grid for the final test

4

Results and Discussion

In this section, the results from the validation test will be discussed. It is divided into three parts. First, there's a performance analysis where the speed and accuracy of the users will be discussed. Second, there's a usage analysis of how the users used the slider visualization during the test. Then, there's a perception analysis for the results of the UEQs questionnaire, and interviews will be discussed.

4.1. Performance Analysis

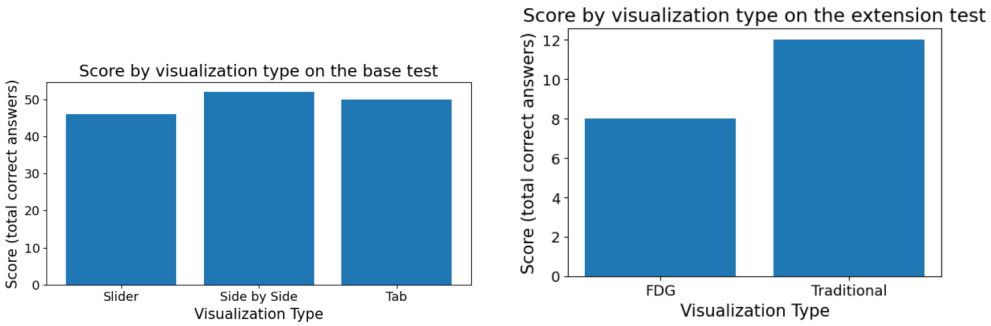
In order to measure the performance of the visualization tool, two metrics are defined. The time it took them to complete each task, and the accuracy in them (whether they had it correct or not).

In total, N_{base} = 31 users participated in the study, N_{ext} = 8 users decided to participate in the extension test. The participants were BSc, MSc, PhD students, and young professionals in different areas of expertise. The users were separated into two groups: experienced and non-experienced, depending on their previous experience with visualization tools for analysis of similar data or similar tools. Experienced users included users who had previous experience in: power grid analysis, visualization systems for networks, visualization systems for geographical exploration in technical areas, general node-link diagram visualization experience, etc. $N_{base_{exp}}$ = 16 users from the base test and $N_{ext_{exp}}$ = 4 users from the extended were stated to be experienced. $N_{base_{noexp}}$ = 15 users from the base test and $N_{ext_{noexp}}$ = 4 users from the extended were stated to not have experience. Since the methodology used a repeated-measures design, each participant did two tasks using each visualization method. This resulted in a total of M_B = 62 measurements per visualization style in the base test, and M_E = 16 measurements for the case of the extension. Table 4.1 shows the summary of the test results by visual style: the number of measurements per visualization style, the average time in seconds, the standard deviation, and the total score.

Visualization style	M	Average Time (s)	Sandard Deviation (s)	Total Score
Slider	62	166.527	87.442	46
Side by Side	62	107.175	76.376	52
Tabs	62	134.025	92.918	50
Force-directed	16	91.248	59.700	8
Traditional SLD	16	124.499	56.554	12

Table 4.1: Visualization summary (all data)

Appendix A contains tables summarizing the results of the performance of each user in all visualization styles. In addition, there are tables summarizing the results when only taking into account the correct answers. This data includes a distinction on whether users had or not previous experience.



(a) Total score per visualization in the base test

(b) Total score per visualization in the extended test

Figure 4.1: Total scores per visualization in both tests.

As a first step, a check on whether there was any significant difference in the accuracy of the participants depending on the visualization they used. Figure 4.1 shows the total scoring in both tests by aggregating the scores of each user per visualization. The score was defined as the number of correct answers the user had per each visualization; therefore, a higher score means a higher accuracy. This shows similar results for the visualizations in the base test (Figure 4.1a) as they all fall in the range between 46 and 52, while there is a higher discrepancy in the case of the extended test, as the scoring for the force-directed and traditional SLD were 8 and 12, respectively (specific values can be seen in Table 4.1). Note that as the experiment used repeated-measures design, the results need to be interpreted taking into account both inter and intra-subject variability. Thus, in order to assess whether there was a significant difference between these, a Friedman test was conducted for comparing the accuracies of the slider, side by side and tab visualizations of the base test, while a Wilcoxon test was done for comparing the accuracies of the transition between the geographical and force-directed, and geographical and traditional in the extended test. Table 4.2 shows the results of these tests, which show evidence that there was no significant effect in accuracy between the visualization methods across the different tests.

User Group	M	P-Value (α = 5%)
All Users (Base test - Friedman)	31	0.549
Experienced (Base test - Friedman)	16	0.761
No Experience (Base test - Friedman)	15	0.168
All Users (Extended test - Wilcoxon)	8	0.157
Experienced (Extended test - Wilcoxon)	4	0.157
No Experience (Extended test - Wilcoxon)	4	0.414

Table 4.2: Results of Friedman and Wilcoxon tests to determine whether there was a significant difference in the accuracy of the participants depending on the visualization they used.

Now, a step-by-step walk-through on the results processing will follow for the aggregate of all of the user data in regard to the speed in completing the tasks. Later, the results of this same process for the case of only the correct answers will follow.

The first step was to assess whether the measurements of the average time of the users to complete the task with each visualization follow a normal distribution. To do so, a Shapiro-Wilk (SW) test is performed on both the averages and the paired differences of the means on the base test. Since only a small number of users agreed to do the extension, the safe approach of not assuming normality in this case is followed. Table 4.3 shows the summary of the results for this test in the base test. In it, it can be seen that the mean times themselves do not appear to follow a normal distribution, as they do not present a p-value larger than 0.05. In the case of the differences, however, it appears that the data does follow a normal distribution by having a p-value larger than 0.05. This is supported by the QQ-plots that show considerable deviations from the reference line in the case of the means, while the differences did have a better fit (Figure 4.2).

Variable	M	W Statistic	p-value	Normality ($\alpha = 0.05$)
Slider mean	31	0.899	0.007	Not normal
Side mean	31	0.815	<0.001	Not normal
Tab mean	31	0.799	<0.001	Not normal
Difference 1–3	31	0.978	0.758	Normal
Difference 1–2	31	0.962	0.329	Normal
Difference 2–3	31	0.974	0.635	Normal

Table 4.3: Shapiro–Wilk test results for base-condition means and paired differences.

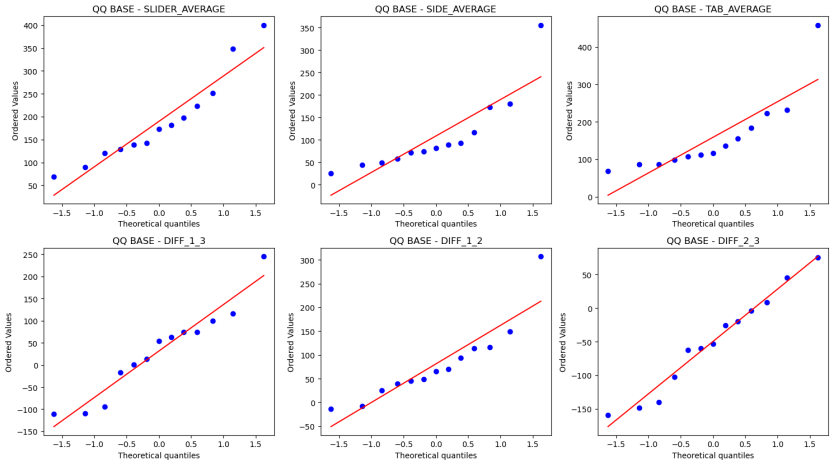


Figure 4.2: QQ plots for the means and paired differences

With this in mind, and given that the procedure had both inter and intra-subject variance, a Friedman test was used to assess whether there are any significant differences in the times of task completion per visualization of the base test. This test resulted in a p-value of 0.001 and a Kendall-W coefficient of 0.22, making it evident that there is asignificant difference. To evaluate this, and since SW showed evidence of normality, t-paired tests were used to identify which alternative had a lower mean time in the base test. Table 4.4 shows these results, where there are significant differences in these means. Particularly, the users were faster when using the side-by-side visualization compared to the other two, while the tab was faster than the slider. There was a moderate effect in the difference in the speed of the tab visualization compared to the other two, as the Cohen's d was close to 0.5. Meanwhile, there was a big effect when comparing the side-by-side and slider visualizations, as the Cohen's d value was 0.896. Regarding the comparison between the force-directed and traditional SLD, as the number of measurements was too small to assume normality, a Wilcoxon test was performed. It resulted in a p-value of 0.0156, which indicates a significant difference, with the force-directed as the faster method. The effect of this difference is big, as the magnitude of the Rank Biserial coefficient is 0.9444.

Comparison	M	p-value ($\alpha = 0.05$)	Cohen's d
Slider - Side	31	< 0.001	0.896
Slider - Tab	31	0.025	0.424
Side - Tab	31	0.016	-0.459

Table 4.4: Paired t-test results for the base conditions, including Cohen's d as a measure of effect size.

This same analysis process was then repeated by separating the user data into two groups depending on whether they had general experience, as marked in the data. In the case of the users with experience, the SW test did not show evidence of a normal distribution on the slider's mean time. A Friedman test followed suit, which did not detect any significant differences (p-value of 0.068) in the task completion times. The Wilcoxon comparison for the extension results did not yield any significant differences either

(p-value of 0.25).

For the users with no experience, the SW test did not show evidence of a normal distribution for the side-by-side or the tab view. The Friedman test then showed evidence of significant differences in the task completion times (p-value of 0.014), with a low effect (Kendall's W of 0.284), and the posterior paired t-test did show significant difference, but only between slider and side-by-side (p-value of 0.0014) and a really big effect (Cohen's d of 1.024), with side by side being the faster method. No significant difference was detected when comparing the force-directed and the traditional SLD (p-value of 0.125).

Finally, a comparison between the means of each of the visualization times and the average duration of the test was made between these two groups. The SW test showed evidence of a normal distribution for the differences of the means of the base test, except for the difference in the mean of the side-by-side mean, so it was evaluated using the Wilcoxon test along with the means of the extension. No test in this part yielded significant differences.

This process was then repeated by taking into account only the user responses that were correct. The summary of this dataset by visualization is in Table 4.5. A first glance at this data shows that, in general, the average time increased for all visualizations except for the force-directed, which was faster in this case. This could be an indication that these users took their time in solving this, taking care to find the correct answer. This is supported by Figure 4.3, where the regression lines show that there is a trend of users that spent a higher amount of time on average had the highest scores. It is important to note that the R^2 value is low for all of the regressions, likely due to the user scores only being able to be 0, 1 and 2, so it is not possible to have a perfect fit.

Visualization style	M	Average Time (s)	STD (s)	Total Score
Slider	46	178.543919	91.987183	46
Side by Side	52	113.982792	79.409379	52
Tabs	50	148.969714	96.233510	50
FDSLD	8	80.880944	51.262874	8
Traditional SLD	12	134.083196	57.423260	12

Table 4.5: Visualization summary (correct answers only)

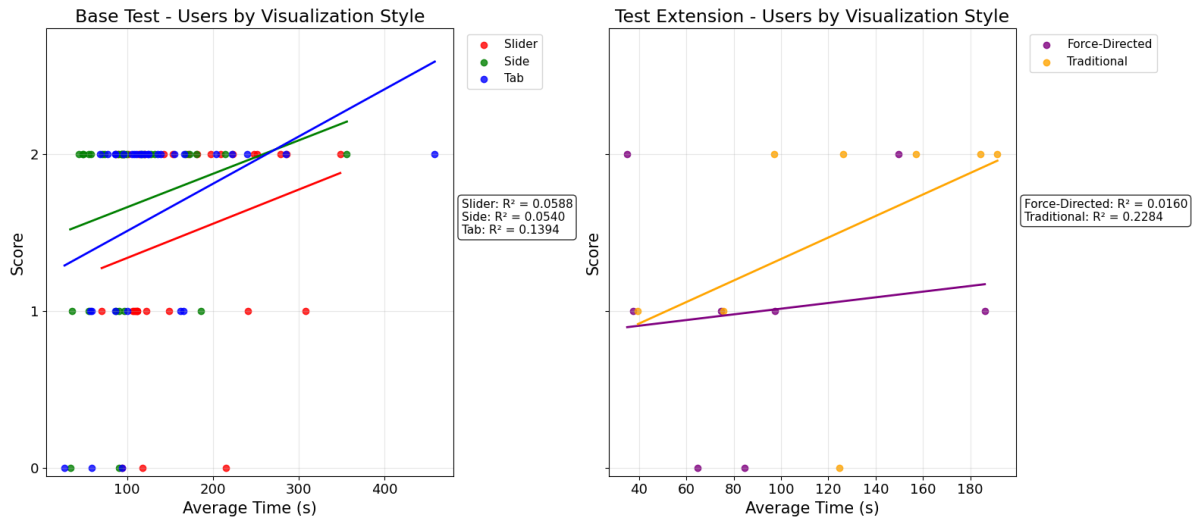


Figure 4.3: Score vs average time for each visualization style in both tests.

A comparison of the mean times per visualization of this pruned dataset was made, following the same steps as the previous one. The first test, comparing the whole dataset, showed evidence of a normal distribution for both the differences and the slider mean time. The Friedman test revealed that there was a significant difference in the task completion times of the three visualizations in the base test (p-value of 0.0019) with a low effect (Kendall's W of 0.241). The paired t-tests only showed evidence of a

significant difference when using the slider, making it faster than the other two. This difference was more pronounced between the slider and the side (Cohen's d of 0.808 compared to 0.460 for the side vs tab). The Wilcoxon test comparing the difference of the means in the extension yielded a significant difference, with the force-directed view being the faster method. Its effect was extremely high, as the Ranking Biserial showed a value of 1.

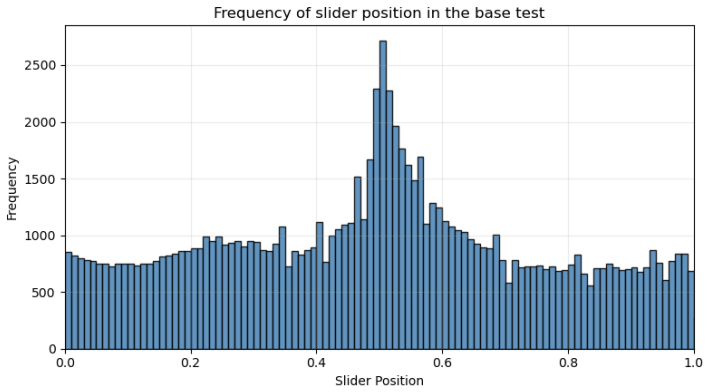
The analysis on the comparisons by experience level of the users yielded similar results to the previous analysis: there was no significant difference between the means of any of the visualization systems for the group of experienced users. The no-experience group showed a significant difference via the Friedman test for the base test, with the side-by-side visualization being faster than the slider (p-value of 0.001 and rank biserial of 0.943), and none for the extension. This comparison had to be done with a Wilcoxon test, as the SW did not yield a normal distribution for the difference of the means of the slider and side. The final comparison between the means of each visualization of both groups yielded no significant results.

In general, there were statistically significant differences in task completion times across visualization styles. This difference, however, must be taken with caution as the sample size is quite small ($N_{base} = 31$), meaning that the study is more sensitive for large effects than small or moderate ones. There was a moderate global effect, as the Friedman tests for the whole group and the non-experienced users subgroup showed significant differences in task completion times with a Kendall's W of at most 0.33. However, observing the paired differences in all the cases where the Friedman test showed significance difference, the biggest effect was observed when comparing the slider and the side-by-side visualization, as the coefficients showed a considerable effect (Cohen's d always higher than 0.8, and rank biserial of 0.943). In other words, the results suggest that, in general, users tended to complete tasks faster when using the side-by-side visualization compared to the slider. However, no significant difference in the mean times was found for the experienced users.

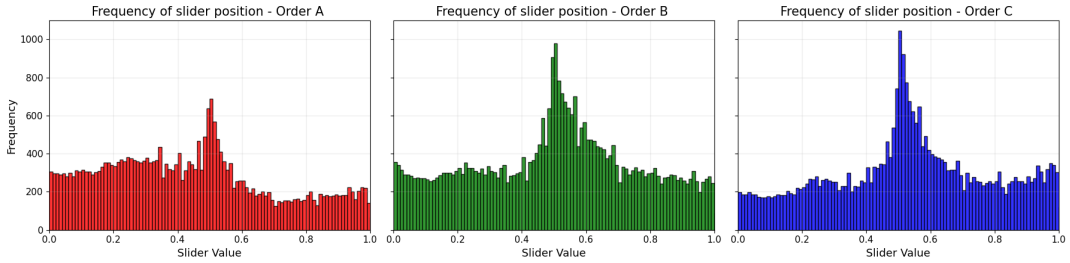
Regarding the test extension, it is important to note that given the smaller sample size of users ($N_{ext} = 8$) the tests are far more sensitive to only detect large effects.. In this case, there was only a significant difference when comparing the whole set of users in both cases (of all data and only using the correct answers data). Particularly, the effect found was large, as the rank biserial coefficient had a magnitude of 0.944 for the whole set of users and 1 for the correct answers only, suggesting that there is a large effect when using the force-directed visualization compared to the traditional SLD, with the former being faster.

4.2. Usage Analysis

Usage metrics of the visualization interactions were taken throughout the test. Specifically, the value of the slider's movements throughout time and the selection of nodes in the grid. These metrics were collected in order to assess the kind of use the users gave to the visualization.



(a) Frequency of the slider position during the base test

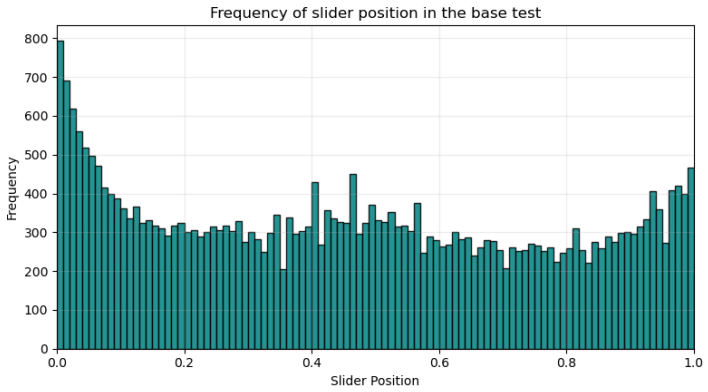


(b) Frequency of the slider position during the base test, divided by group

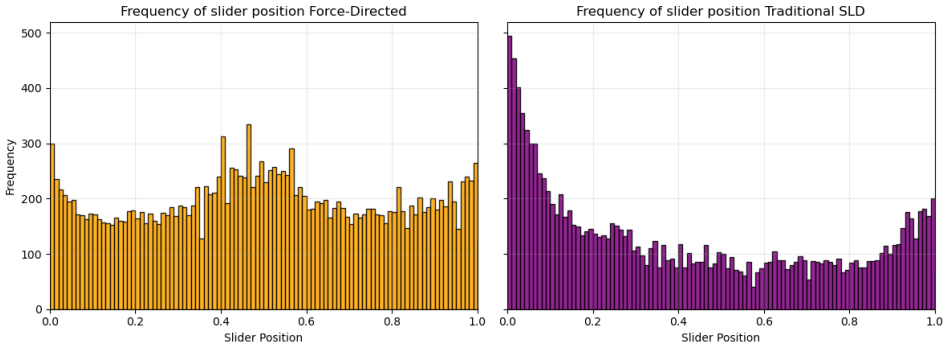
Figure 4.4: Frequency of the slider position in the base test

Figure 4.4 shows the frequency of the position of the slider throughout the base test, measured when users use it. Figure 4.4a shows the frequency for all users in the base test. There is a high frequency towards the middle, the position representing the geographical view. This is to be expected, as per the task instructions, they had to identify which nodes are inside the area and then verify the distance of tentative answers. Furthermore, there seems to be no clear preference for either side, as the diagram appears to be quite symmetrical. One thing to note is that the valley-like structures on the right side (towards the traditional SLD) and near the end of the left side (towards the force-directed, at around a slider position of 0.1) can be indications that the user moved the slider faster than the system could detect, meaning that they were not interested in these in-between positions, but rather only on the endpoints. However, the force-directed side has a mountain-like structure between the positions of 0.2 and 0.4. This means that they had a slower transition in this area, possibly with some back-and-forth movement, meaning that there was some interest in this portion of the graph.

Figure 4.4b shows the frequency of the slider position for the base test separated by group. As mentioned in Section 3.5, group A (red) was presented with the slider visualization first, group B (green) last, and group C (blue) second. Users who used the slider visualization first tended to use the left side of the slider more than the right side, explained by the higher frequency of use on the left side. Particularly, this increase in use is similar to the increase in frequency shown in Figure 4.4a at around 0.2 and 0.4, meaning that these users were interested in the in-between values of the force-directed view. No increase in frequency was observed on the right side. Similarly, orders B and C show a more equal use of both sides, but they also see an increase in frequency near the 0.25-0.3 position, while none is shown on the right side. Finally Order C presents a valley-like structure on the right side, indicating that these users tended to pass quickly through the right side, only slowing down near the end. Order B presents a decrease in the frequency from the initial position of 0.5 towards the right side. There is, however, no increase reaching the end. And order A does show a small valley-like structure towards the right side.



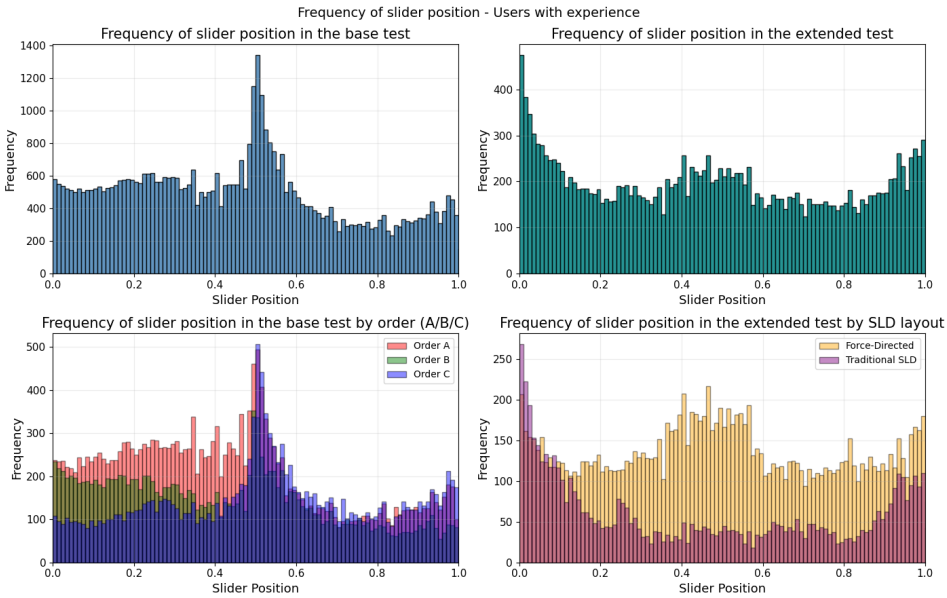
(a) Frequency of the slider position during the extended test



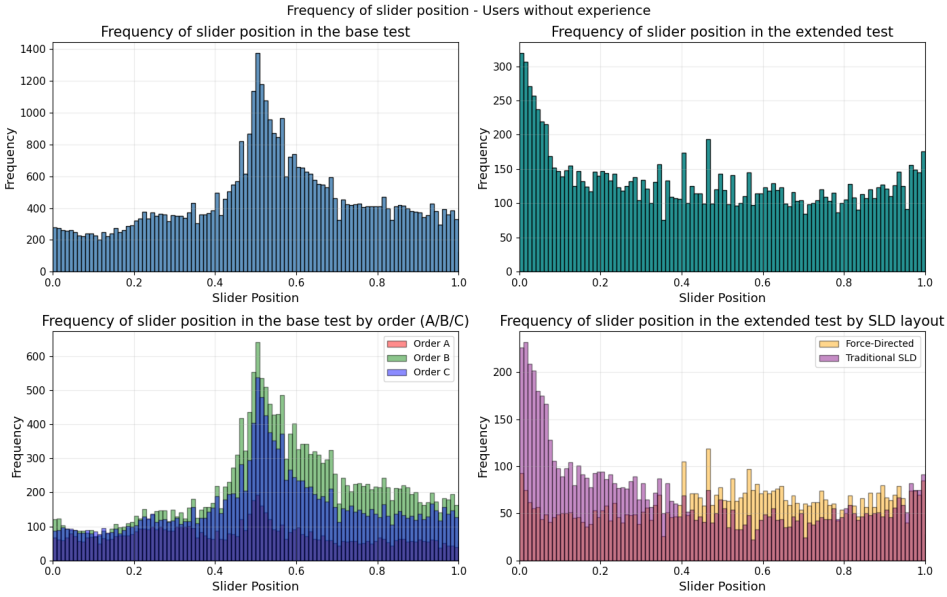
(b) Frequency of the slider position during the extended test, divided by SLD layout

Figure 4.5: Frequency of the slider position in the extended test

Figure 4.5 shows similar diagrams for the extended test. Figure 4.5a shows the aggregated data for the extended test, while Figure 4.5b shows the frequency separated by SLD layout (FDSLD vs traditional). The aggregated diagram shows a bump consistent with the left side of the diagrams in Figure 4.4, which means that, in general, users tended to have quite an intensive use of the visualized slider in those positions. This bump is also present in the diagram showing the position for visualization with the force-directed layout. This is quite consistent with the results from the previous diagrams, in which the bump tended to exist towards the left side. On the other hand, in the case of the frequency of the position in the visualization with the traditional layout, a valley-like structure is present. This means that users were likely to just speed away during the middle portions of the diagram and focus just on the endpoints. However, it is of note that the left side of this diagram does have a lot of movement, which means that the users tended to use small movements of the slider near the starting position, just to move the positions a bit, meaning that just a small movement was enough to gather the insights needed.



(a) Frequency of the slider position for experienced users throughout all tests.



(b) Frequency of the slider position for experienced users throughout all tests.

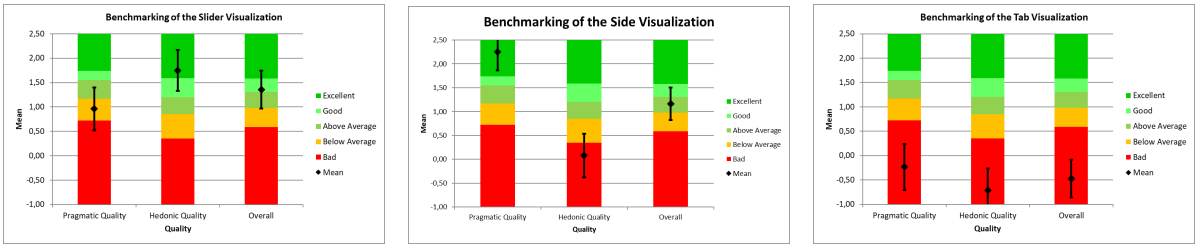
Figure 4.6: Frequency of the slider position separated by experience.

Finally, Figure 4.6 shows the use of the slider separated by the experience of users. In general, this figure shows a noticeable difference in the behavior of the users when using the slider, depending on their experience level: experienced users tended to spend more time in the intermediate between the geographical layout and the FDSLD compared to the users in the no-experience group, as it can be seen in the bottom left plot of each of figures 4.6a and 4.6b. Also, note the experienced users had a similar behavior in the transition to the traditional side, as the valley-like structure is present there, and is more pronounced. This is supported by the plot for the differences in the extended test, as there is a clear increase in use for the slider in the middle parts for the visualization with only the force-directed compared to the traditional, which presented a noticeable valley-like structure. Also, the non-experienced group had a noticeably different behavior, as in the base test they spent more time using the transition towards the traditional side. Also, during the extension test, they showed a more constant frequency of the slider positions, meaning that they did the transition at similar speeds, in the

force-directed case. On the other hand, for the traditional case, the valley-like structure is present, but presents a large tail near the geographical position, which means that non-experienced users tend to use more the intermediate transitions close to the geographical position in a noticeable manner.

4.3. Perception Analysis

This section will discuss the User Experience Questionnaire results, accompanied by insights from the interviews.



(a) UEQ Benchmarking on the slider **(b)** UEQ Benchmarking on the side **(c)** UEQ Benchmarking on the tab

Figure 4.7: UEQ benchmarking on the base test visualizations

Figure 4.7 shows the results of the benchmarking procedure introduced in [46]. This benchmark is based on data from 468 studies with a total of more than 20 thousand data points. This data, however, represents a wide range of products, which means that it is not specifically tailored for this application. However, it is still a food measure to interpret the general perception of the users. In general, the slider is shown to have an overall food performance with an excellent hedonic quality and a below average pragmatic quality. This means that users found this visualization was interesting and enjoyable to use, while they perceived it not to be really efficient. In the case of the side-by-side visualization, it had a good performance. In contrast with the slider, users found this visualization overwhelmingly efficient, with an excellent performance in the pragmatic quality, which is congruent to the results from Section 4.1. With regards to the hedonic quality, users found that it was not really enjoyable or interesting to use. Finally, regarding the tab visualization, it performed badly in all qualities, which is congruent with the interview data that will be exposed at the end of the section.

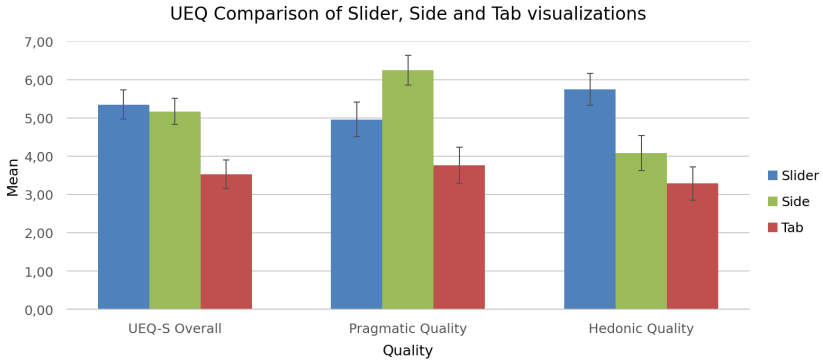


Figure 4.8: UEQ comparison in the base test

Figure 4.8, and tables 4.6 and 4.7 show the result of comparing the Slider visualization to both other alternatives. These comparisons show that the Slider visualization was better perceived by the users than the Tab visualization, showing statistical significance in all three aspects. Regarding the slider and side comparisons, there was no overall difference. However, there was a significant individual difference in the qualities: the slider performed better in the hedonic quality, while the side performed better in the pragmatic.

Metric	p-value	Result ($\alpha = 0.05$)
UEQ-S Overall	< 0.001	Significant difference
Pragmatic Quality	0.0006	Significant difference
Hedonic Quality	< 0.001	Significant difference

Table 4.6: Statistical test results for UEQ-S scores (Slider vs tab).

Metric	p-value	Result ($\alpha = 0.05$)
UEQ-S Overall	0.4720	No significant difference
Pragmatic Quality	0.0001	Significant difference
Hedonic Quality	< 0.001	Significant difference

Table 4.7: Statistical test results for UEQ-S scores (Slider vs Side).

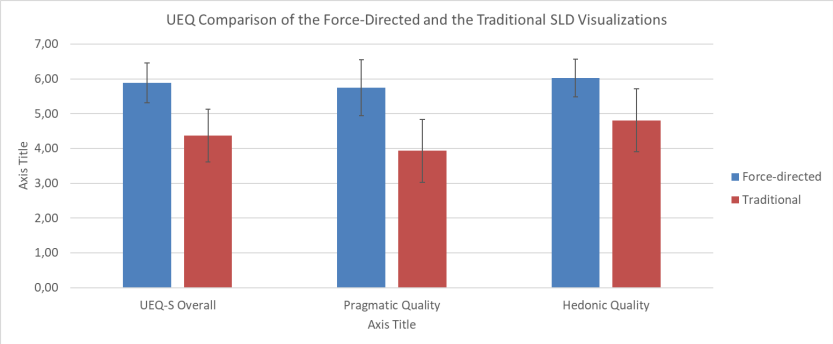
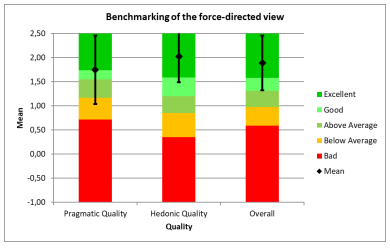


Figure 4.9: UEQ Comparison of the force-directed and the Traditional SLD approaches

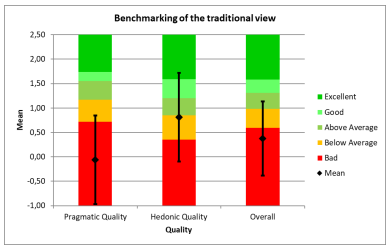
Figure 4.9 and Table 4.8 do this same process on the comparison between the force-directed and the traditional SLD. In this case, the force-directed had a significantly better perception compared to the traditional SLD. Furthermore, Figure 4.10 shows the benchmarking results on the extended test visualizations. In this case, it can be seen that the force-directed view had an overwhelmingly better performance, it being excellent in all qualities, while the traditional view had a bad overall and pragmatic performance, with a below average hedonic quality.

Metric	p-value ($\alpha = 0.05$)
UEQ-S Overall	0.008
Pragmatic Quality	0.009
Hedonic Quality	0.044

Table 4.8: Statistical test results for UEQ-S scores (force-directed vs Traditional).



(a) UEQ Benchmarking on the force-directed view



(b) UEQ Benchmarking on the traditional view

Figure 4.10: UEQ benchmarking on the extended test visualizations

Next, a comparison of the perception of the slider between the experienced and non-experienced user groups was made. The results can be seen in Table 4.9 and Figure 4.11, that show that there is no significant difference between the two groups.

Metric	p-value ($\alpha = 0.05$)
UEQ-S Overall	0.0078
Pragmatic Quality	0.0085
Hedonic Quality	0.0441

Table 4.9: Statistical test results for UEQ-S scores comparison of the slider perception between the experienced and non-experienced users.

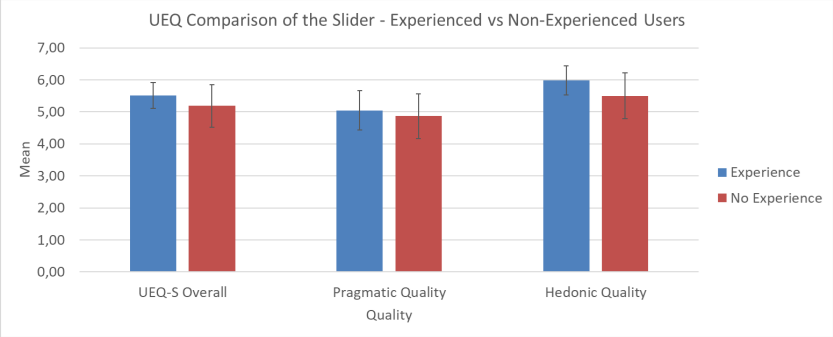


Figure 4.11: UEQ Comparison of the slider between the experienced and non-experienced users

In general, these results are backed by the comments of the users in the interviews. Appendix B has a general summary of all common user comments. Overall, users had a positive perception of the slider: 23 had positive comments: it was enjoyable (8), it was useful to be able to follow items in the transition (13) and intermediate values (7), and that it was helpful to had all information in one view (4). 9 users, however, had a not that positive impression of the slider: 7 mentioned that it mixes the components too much, 1 mentioned that it required a lot of attention, and another one said that it was not useful at all. Regarding the force-directed and traditional layouts, 13 users had a better perception of the force-directed, while 2 preferred the topological. 6 users did not use the force-directed enough to have an opinion. Finally, 28 users mentioned that they had a clear preference for the side, as it gave them all of the information at the same time. Everyone had negative comments about the tab, as the change of context made it hard to remember the information from the previous layout.

5

Conclusion

This research had the main objective of creating a tool that allowed users to see two different representations of the power grid in the same view, focusing on a geographical and topology-oriented representations. A slider-based feature that transforms between the different representations was found to be an effective way to do so. This feature allows users to make a smooth and controlled transition between the different layouts, enabling them to get geographical information of the components from the geographical layout, and turn to the topology to have a clearer understanding of the connections. The tool included two different topological representations: one that followed traditional SLD placement guidelines (more structured and following a clear tree structure) and a force-directed inspired one that made the topology clearer while keeping some geospatial congruency.

A validation user study was executed to assess the effectiveness of the designed tool. In the study, a set of 31 users was tested in tasks comparing the proposed visualization with two other methods inspired by current usage: a method that displayed both representations side-by-side, and a representation that emulated having the two views in different tabs, making the users change between them using buttons. In this set, 16 users had experience in using visualization tools for problems of similar nature, not power grid related necessarily. An extension of the test was also done by 8 of these users, to assess the difference between the two different topological layouts in the slider view.

In general, it can be said that a slider-based visualization is a potentially effective way to merge a geographical and a topological representation of the grid. Evidence that the use of this visualization led to higher completion times for the whole set of users when comparing it to other visualizations inspired by methods currently in use by operators was found. This difference was particularly strong when comparing it to the side-by-side visualization. However, when looking only into the users with expertise in similar areas, there was no significant difference in these times. Furthermore, no significant difference in accuracy was found when using the slider visualization compared to the other two visualizations. Also, the fact that users had a trend to have more movement in the transitions between the geographical and force-directed views show that it might not be necessary to do a complete transition between the two representations. This is in line with this finding, as the slider feature is what allows users to have control over the transition, enabling them to stop or go back and forth in these positions. Finally, the fact that the users had a more positive perception of the slider-based visualization compared to the other two methods in the hedonic quality indicate that there might be more inclined or receptive to use it. This is particularly true when comparing this visualization to the Tab visualization, as the latter was not perceived as effective or enjoyable by the users. This is congruent with the recommendation of combining the different applications proposed by Afzal et al. [1], as the tab visualization was designed to emulate the use of the two different applications in different tabs, making the user change between them using buttons. The interview comments also support this, since all users had negative comments about the tab visualization due to the cognitive load of having to remember the information from the previous layout.

When comparing this visualization with the one presented by Hoang et al. [18] there are a couple of

points to note. First of all, both visualizations had a positive reception by the users that participated in the study. Particularly, there were comments stating that it is useful to have access to both views to make the mental connection between the geographical and topological representation of the grid. However, the visualization presented by Hoang et al. presents two key limitations: only making a qualitative study, and the method used to transition between the two layous might not be the most appropriate. The method in question is based on using a button that triggers the transition, in a similar manner to the tab visualization, with the difference that the method presented by Hoang et al. instead of doing the transition in one step, creates an animation that disassembles the current layout into their minimal components, to then assemble it again in the new layout. This method seemed to generate some mixed sentiment as some users did mention that it was intuitive, while another one mentioned that it was confusing as all components move together. Also, it was stated that pausing the transition in the middle does not give any information, as nothing is in position. These problems are nonexistent in the slider visualization, as users have full control of the transition, making it less confusing, and, in the case of the transition to the force-directed layout, the intermediate steps do give relevant information as the components stay connected and are kept close to their real-world positions.

5.1. Limitations and Future Work

There were some limitations to the study that might be worth taking into account in future work.

Firstly, the use of linear interpolation as a transition method while being a direct way of showing the transition between the layouts, might not be the best in all cases. For the force-directed case, a linear interpolation seems to work well, as the total amount of movement is relatively small since the force-directed layout kept some geospatial congruency, making the transition smoother and thus easier to read, while also not having that many crossings of components. In the case of the traditional as this layout had to do more pronounced changes of the position of the components, by linealy interpolating the positions the nodes ended up having a lot of crossings and doing a larger transition. This is mainly supported by the usage results, as the users tended to have more movement in the transition to the force-directed compared to the traditional, as well as the users having a more positive perception of the force-directed compared to the traditional. Future work could focus on looking into different transition methods that might be more appropriate depending on the layouts.

Secondly, the scale of the user study was relatively small as it only had a total of 31 participants, making it more difficult to reliably identify small and moderate effects in the results. Furthermore, the task designed for the final study might have not been too representative of actual tasks performed by operators. This was due to a limitation of not being able to count with grid operators to participate in the study. While the input of the PhD students in the interviews was valuable for the task designs, it resulted in tasks that are might not be completely representative of actual work done by operators in their day to day. Also, since the users in the study were not real operators and had to be recruited to participate in the user study, the tasks had to be designed using radial grids of moderate size to ensure that they would be able to complete the tasks in a reasonable amount of time. Therefore, even though the results show that the slider visualization was a potentially effective way of presenting both representations of the grid to users, it might not be applicable to real-world scenarios. Future work should include grid operators in the design and validation parts in order to both ensure that the tasks are more representative of real world work and have the ability to use larger and more complex grids for the validation studies. This would allow for a more accurate assessment of the tool and its ability to be used in real-world scenarios.

Finally, it is worth to mention that this visualization style could be useful beyond the use by grid operators as, by shown in the feedback of the visualization presented by Hoang et al. [18], making these connections between a technical diagram and their geographical representation could be useful for learning or non-technical users. Furthermore, there could be many other applications that could benefit from having a geographical and topological context in the same view in domains different than the power grid. Some examples of this could be visualizing people's routines (which places they tend to visit) for epidemiological studies, visualizing the paths that autonomous robots follow between different landmarks.

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A

Efficiency Results

Table A.1: Base users summary (all responses)

User ID	Total Time (s)	Total Score (points)	Experienced User
105181	1038.56	6	No
118668	416.93	5	Yes
137842	1168.59	6	Yes
161814	620.19	5	Yes
163861	521.24	6	No
216011	634.91	5	No
241562	845.11	5	Yes
312441	1112.42	5	No
335049	935.09	6	Yes
355971	458.23	4	No
371519	428.45	3	No
371966	1029.00	5	Yes
372655	2325.66	6	No
406209	1160.72	6	Yes
446357	590.27	5	No
495468	927.26	5	Yes
508050	629.85	5	No
611925	811.25	6	No
634253	509.57	5	Yes
660854	894.49	5	Yes
661509	724.23	4	Yes
699868	715.66	5	No
726890	365.44	1	Yes
856680	1134.32	6	No
862791	664.04	5	Yes
916490	1339.53	6	Yes
939606	487.09	4	No
950023	913.11	5	No
954027	490.30	3	No
959977	588.85	5	Yes
961582	798.70	0	Yes

Table A.2: Base users summary (correct responses only)

User ID	Total Time (s)	Total Score (points)	Experienced User
105181	1038.56	6	No
118668	370.65	5	Yes
137842	1168.59	6	Yes
161814	538.09	5	Yes
163861	521.24	6	No
216011	510.06	5	No
241562	747.88	5	Yes
312441	896.09	5	No
335049	935.09	6	Yes
355971	336.12	4	No
371519	220.81	3	No
371966	823.02	5	Yes
372655	2325.66	6	No
406209	1160.72	6	Yes
446357	449.66	5	No
495468	763.78	5	Yes
508050	539.60	5	No
611925	811.25	6	No
634253	471.50	5	Yes
660854	795.14	5	Yes
661509	487.67	4	Yes
699868	615.37	5	No
726890	67.84	1	Yes
856680	1134.32	6	No
862791	559.11	5	Yes
916490	1339.53	6	Yes
939606	322.21	4	No
950023	838.64	5	No
954027	244.26	3	No
959977	556.13	5	Yes

Table A.3: Extended users summary (all responses)

User ID	Total Time (s)	Total Score (points)	Experienced User
105181	1440.64	9	No
137842	1782.38	10	Yes
355971	607.26	7	No
611925	1134.73	8	No
660854	1635.14	8	Yes
916490	1917.05	9	Yes
939606	713.61	6	No
961582	1217.58	0	Yes

Table A.4: Extended users summary (correct responses only)

User ID	Total Time (s)	Total Score (points)	Experienced User
105181	1348.82	9	No
137842	1782.38	10	Yes

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User ID	Total Time (s)	Total Score (points)	Experienced User
355971	444.53	7	No
611925	1005.29	8	No
660854	1285.11	8	Yes
916490	1785.91	9	Yes
939606	415.41	6	No

Table A.5: Base users – Slider data (all responses)

User ID	Slider Mean Time (s)	Slider SD (s)	Slider Score (points)	Experienced User
105181	222.80	59.97	2	No
118668	94.98	57.00	2	Yes
137842	248.06	35.14	2	Yes
161814	113.67	1.70	2	Yes
163861	142.91	70.23	2	No
216011	149.04	34.21	1	No
241562	209.18	51.98	2	Yes
312441	308.27	130.03	1	No
335049	278.41	185.29	2	Yes
355971	107.90	44.06	1	No
371519	106.84	24.57	1	No
371966	240.55	48.88	1	Yes
372655	348.33	62.35	2	No
406209	286.18	1.88	2	Yes
446357	89.34	62.58	2	No
495468	153.68	7.33	2	Yes
508050	109.72	27.55	1	No
611925	181.69	24.88	2	No
634253	87.06	33.41	2	Yes
660854	111.34	16.95	1	Yes
661509	118.28	33.88	0	Yes
699868	120.75	29.43	2	No
726890	122.00	76.59	1	Yes
856680	250.93	104.73	2	No
862791	111.53	9.34	1	Yes
916490	170.70	32.87	2	Yes
939606	70.37	2.31	1	No
950023	197.59	71.78	2	No
954027	94.47	68.67	0	No
959977	100.71	37.70	2	Yes
961582	215.05	102.24	0	Yes

Table A.6: Base users – Side data (all responses)

User ID	Side Mean Time (s)	Side SD (s)	Side Score (points)	Experienced User
105181	73.92	26.44	2	No
118668	55.13	14.72	2	Yes
137842	96.38	5.74	2	Yes
161814	95.90	62.11	2	Yes
163861	49.03	5.47	2	No
216011	57.44	7.11	2	No

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User ID	Side Mean Time (s)	Side SD (s)	Side Score (points)	Experienced User
241562	96.37	1.23	1	Yes
312441	92.92	32.80	2	No
335049	93.33	15.14	2	Yes
355971	35.50	13.94	1	No
371519	48.30	31.82	2	No
371966	168.71	72.25	2	Yes
372655	356.04	222.98	2	No
406209	127.79	50.93	2	Yes
446357	43.68	29.03	2	No
495468	185.96	31.79	1	Yes
508050	89.59	16.78	2	No
611925	116.08	65.01	2	No
634253	90.25	73.79	1	Yes
660854	132.47	18.65	2	Yes
661509	118.50	67.83	2	Yes
699868	71.46	38.34	2	No
726890	33.66	21.78	0	Yes
856680	180.77	28.38	2	No
862791	99.65	44.26	2	Yes
916490	214.40	31.89	2	Yes
939606	87.38	7.78	1	No
950023	172.83	10.05	2	No
954027	93.78	89.99	2	No
959977	54.87	31.32	1	Yes
961582	90.35	48.60	0	Yes

Table A.7: Base users – Tab data (all responses)

User ID	Tab Mean Time (s)	Tab SD (s)	Tab Score (points)	Experienced User
105181	222.55	89.90	2	No
118668	58.35	17.07	1	Yes
137842	239.85	178.19	2	Yes
161814	100.52	26.05	1	Yes
163861	68.67	32.28	2	No
216011	110.97	33.63	2	No
241562	117.01	15.58	2	Yes
312441	155.02	46.02	2	No
335049	95.80	8.91	2	Yes
355971	85.71	8.06	2	No
371519	59.09	27.91	0	No
371966	105.24	12.56	2	Yes
372655	458.46	162.72	2	No
406209	166.39	39.70	2	Yes
446357	162.12	30.42	1	No
495468	123.99	47.70	2	Yes
508050	115.61	60.00	2	No
611925	107.85	4.33	2	No
634253	77.48	6.39	2	Yes
660854	203.44	29.94	2	Yes
661509	125.34	38.57	2	Yes
699868	165.63	92.40	1	No
726890	27.07	3.12	0	Yes

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User ID	Tab Mean Time (s)	Tab SD (s)	Tab Score (points)	Experienced User
856680	135.46	49.57	2	No
862791	120.84	11.30	2	Yes
916490	284.67	93.94	2	Yes
939606	85.80	4.35	2	No
950023	86.13	16.49	1	No
954027	56.90	0.26	1	No
959977	138.84	95.87	2	Yes
961582	93.95	50.57	0	Yes

Table A.8: Base users – Slider data (correct responses only)

User ID	Slider Mean Time (s)	Slider SD (s)	Slider Score (points)	Experienced User
105181	222.80	59.97	2	No
118668	94.98	57.00	2	Yes
137842	248.06	35.14	2	Yes
161814	113.67	1.70	2	Yes
163861	142.91	70.23	2	No
216011	173.23	0	1	No
241562	209.18	51.98	2	Yes
312441	400.21	0	1	No
335049	278.41	185.29	2	Yes
355971	139.06	0	1	No
371519	124.21	0	1	No
371966	275.12	0	1	Yes
372655	348.33	62.35	2	No
406209	286.18	1.88	2	Yes
446357	89.34	62.58	2	No
495468	153.68	7.33	2	Yes
508050	129.21	0	1	No
611925	181.69	24.88	2	No
634253	87.06	33.41	2	Yes
660854	123.33	0	1	Yes
661509	—	—	0	Yes
699868	120.75	29.43	2	No
726890	67.84	0	1	Yes
856680	250.93	104.73	2	No
862791	118.14	0	1	Yes
916490	170.70	32.87	2	Yes
939606	68.73	0	1	No
950023	197.59	71.78	2	No
954027	—	—	0	No
959977	100.71	37.70	2	Yes

Table A.9: Base users – Side data (correct responses only)

User ID	Side Mean Time (s)	Side SD (s)	Side Score (points)	Experienced User
105181	73.92	26.44	2	No
118668	55.13	14.72	2	Yes
137842	96.38	5.74	2	Yes
161814	95.90	62.11	2	Yes

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User ID	Side Mean Time (s)	Side SD (s)	Side Score (points)	Experienced User
163861	49.03	5.47	2	No
216011	57.44	7.11	2	No
241562	95.50	0	1	Yes
312441	92.92	32.80	2	No
335049	93.33	15.14	2	Yes
355971	25.65	0	1	No
371519	48.30	31.82	2	No
371966	168.71	72.25	2	Yes
372655	356.04	222.98	2	No
406209	127.79	50.93	2	Yes
446357	43.68	29.03	2	No
495468	208.45	0	1	Yes
508050	89.59	16.78	2	No
611925	116.08	65.01	2	No
634253	142.43	0	1	Yes
660854	132.47	18.65	2	Yes
661509	118.50	67.83	2	Yes
699868	71.46	38.34	2	No
726890	—	—	0	Yes
856680	180.77	28.38	2	No
862791	99.65	44.26	2	Yes
916490	214.40	31.89	2	Yes
939606	81.88	0	1	No
950023	172.83	10.05	2	No
954027	93.78	89.99	2	No
959977	77.02	0	1	Yes

Table A.10: Base users – Tab data (correct responses only)

User ID	Tab Mean Time (s)	Tab SD (s)	Tab Score (points)	Experienced User
105181	222.55	89.90	2	No
118668	70.43	0	1	Yes
137842	239.85	178.19	2	Yes
161814	118.94	0	1	Yes
163861	68.67	32.28	2	No
216011	110.97	33.63	2	No
241562	117.01	15.58	2	Yes
312441	155.02	46.02	2	No
335049	95.80	8.91	2	Yes
355971	85.71	8.06	2	No
371519	—	—	0	No
371966	105.24	12.56	2	Yes
372655	458.46	162.72	2	No
406209	166.39	39.70	2	Yes
446357	183.64	0	1	No
495468	123.99	47.70	2	Yes
508050	115.61	60.00	2	No
611925	107.85	4.33	2	No
634253	77.48	6.39	2	Yes
660854	203.44	29.94	2	Yes
661509	125.34	38.57	2	Yes
699868	230.97	0	1	No

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User ID	Tab Mean Time (s)	Tab SD (s)	Tab Score (points)	Experienced User
726890	—	—	0	Yes
856680	135.46	49.57	2	No
862791	120.84	11.30	2	Yes
916490	284.67	93.94	2	Yes
939606	85.80	4.35	2	No
950023	97.79	0	1	No
954027	56.71	0	1	No
959977	138.84	95.87	2	Yes

Table A.11: Extended users – FDSLD data (all responses)

User ID	FDSLD Mean Time (s)	FDSLD SD (s)	FDSLD Score (points)	Experienced User
105181	74.72	24.17	1	No
137842	149.80	7.11	2	Yes
355971	34.98	3.77	2	No
611925	64.72	43.06	0	No
660854	186.11	91.32	1	Yes
916490	97.32	47.82	1	Yes
939606	37.61	3.94	1	No
961582	84.72	35.54	0	Yes

Table A.12: Extended users – Traditional data (all responses)

User ID	Traditional Mean Time (s)	Traditional SD (s)	Traditional Score (points)	Experienced User
105181	126.32	21.93	2	No
137842	157.10	34.86	2	Yes
355971	39.54	1.54	1	No
611925	97.02	41.28	2	No
660854	184.22	45.90	2	Yes
916490	191.44	18.83	2	Yes
939606	75.65	24.43	1	No
961582	124.72	50.69	0	Yes

Table A.13: Extended users – FDSLD data (correct responses only)

User ID	FDSLD Mean Time (s)	FDSLD SD (s)	FDSLD Score (points)	Experienced User
105181	57.63	0	1	No
137842	149.80	7.11	2	Yes
355971	34.98	3.77	2	No
611925	—	—	0	No
660854	121.53	0	1	Yes
916490	63.51	0	1	Yes
939606	34.82	0	1	No

Table A.14: Extended users – Traditional data (correct responses only)

User ID	Traditional Mean Time (s)	Traditional SD (s)	Traditional Score (points)	Experienced User
105181	126.32	21.93	2	No
137842	157.10	34.86	2	Yes
355971	38.45	0	1	No
611925	97.02	41.28	2	No
660854	184.22	45.90	2	Yes
916490	191.44	18.83	2	Yes
939606	58.38	0	1	No

B

Full User Comments

Table B.2: Comments said by each participant.

used extension	prior experience	user id	coded comments
False	True	661509	1 2 3
False	True	634253	4 5 6 2 3
False	True	241562	7 2 6 5 8 4
False	True	495468	2 8 3 9 2 4
False	False	371519	9 3 2 4 6
False	False	163861	7 2 4 6
False	False	950023	7 3 2 4 5 8
False	False	216011	7 3 2 10 1
False	False	954027	3 2 1 10
False	False	856680	3 7 2 1 5 10
False	True	406209	3 1 11 2
False	True	726890	3 7 5 2 10
False	True	371966	2 3 8 4
False	True	161814	3 2 4 8
False	False	508050	7 2 12 13 14
False	True	959977	3 2 15 8 10 14
False	False	699868	3 16
False	True	118668	3 8 5 10
True	True	961582	3 14 2 4 6 15
False	False	446357	3 2 6 4
True	True	660854	3 2 8 5 15 10 17 18 19
True	False	939606	3 7 2 5 10 18
True	False	355971	3 7 2 1 10 20 18
False	True	862791	3 7 2 15 4
False	False	372655	3 7 12 2 54
True	False	105181	3 7 2 5 11 10 18
False	True	335049	3 7 2 14 15
True	True	916490	3 7 5 6 21 18 12
True	False	137842	3 7 2 5 14 17 18
False	False	312441	3 2 1 5 10
True	True	611925	3 2 5 12 14 18

comment code	comment text	all users	experience	no experience
1	Slider mixes everything a lot	7	2	5
2	Side-by-side clear to view information	28	14	14
3	Tab difficult to follow loss of context	28	15	13
4	Force-directed easy to understand	11	7	4
5	Slider useful to follow items	13	7	6
6	Slider useful for intermediate steps	7	4	3
7	Tab tedious to use	15	5	10
8	Slider interesting or enjoyable	8	7	1
9	Slider useful for learning	2	1	1
10	Traditional better than force-directed	11	4	7
11	Slider neither helped nor obstructed	2	1	1
12	Slider helpful all in one view	4	2	2
13	Intermediate view not very useful	1	0	1
14	Did not use force-directed much	6	4	2
15	Slider required learning curve	5	5	0
16	Slider not useful	1	0	1
17	Slider perception improved after extension	2	1	1
18	Force-directed perception improved after extension	7	3	4
19	Traditional hard to understand	1	1	0
20	Slider requires a lot of attention	1	0	1
21	Force-directed and traditional useful in different ways	1	1	0

Table B.1: Frequency of the common comments.