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Category	Min	Max	Chosen
Requirement Analysis and Design	0	20	5
Theoretical Analysis	0	25	0
Experiment Design and Execution	0	20	20
System Development and Implementation	0	15	0
Results, Findings and Conclusion	10	20	20
Aim Formulation and Background Work	10	15	15
Quality of Paper Writing and Presentation	10		10
Adherence to Project Proposal and Quality of Deliverables	10		10
<i>Overall General Project Evaluation (this section allowed only with motivation letter from supervisor)</i>	0	10	
Total marks	80		80

Visualising the Network Topology of National Research and Education Networks in Africa

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ABSTRACT

Previous research on National Research and Education Networks (NRENs) in Africa has shown high latency in traffic exchanged between networks, with 75% of this traffic taking circuitous routes through Europe. Possible reasons for this high latency is lack of peering relationships between NRENs, which can be solved by making use of Internet Exchange Points (IXPs).

In this paper, we presented the creation and design of a geospatial visualisation showing the network structure of African NRENs using traceroute data for network topology discovery. Such a visualisation may aid in the decision-making process of identifying the placement of Internet Exchange Points. Several dimensions of data are displayed in the visualisation including the location of Internet Exchange Points, physical fibre cables and the traceroute information collected.

We assessed the visualisation's effectiveness and accuracy at communicating the network topology of African NRENs and routes of potential traffic traversal. A user centered design approach was used to develop the visualisation and usability tests conducted to evaluate the design in terms of effectiveness, accuracy and usability using the metric of successful task completion and the SUS scale.

CCS Concepts

- **Human-centred computing** → **Visualization**
- **Networks** → **Network structure**

Keywords

National Research and Education Networks; Network Topology Visualisation; Geospatial Visualisation; Information Visualisation; Information Visualisation Application, Data Visualisation; Network Topology Discovery; Traceroute

1. BACKGROUND AND INTRODUCTION

A National Research and Education Network (NREN) is a mesh of interconnected networks that supports the needs of education and research communities in a country [20]. In order to facilitate better research and communication, NRENs aim to reduce latencies between educational institutions, promote bandwidth sharing and improve traffic engineering [20].

This report was completed as part of a Bachelor of Science Honours degree in Computer Science at the University of Cape Town in 2015. For more information about this project including the literature review and project proposal, please see:

<http://people.cs.uct.ac.za/~snbros001/AfriNRENWeb2/>

Previous research on National Research and Education Networks in Africa has shown that 75% of traffic originating from and destined to African institutions traverse circuitous routes through Europe [11]. This contributes to a high latency in traffic exchange in and between African NRENs [11]. Latency or round trip time (RTT) is a measurement of the time it takes for a packet to move from its source to its destination and for the receiver to acquire the acknowledgement packet [11]. Thus, latency has an effect on network performance, which is of particular importance to NRENs that facilitate cross-border research collaborations, where it is likely that data needs to be transmitted at high speeds [20].

Possible reasons for these high latencies are a lack of peering or physical interconnectivity between African NRENs [11][24] [51]. Peering is when different Internet Service Providers (ISPs) exchange data between their networks at an Internet Exchange Point (IXP) [36][38]. This lack of peering is an issue that the regional (eastern and southern Africa) research and education network, UbuntuNet Alliance, has been trying to address by setting up Internet Exchange Points (IXPs) [11] [24][51].

Despite an increase in the establishment of national IXPs in Africa, high latencies still occur indicating a need for further research into the network topology of NRENs. The collection of traceroute data for logical topology discovery is therefore necessary in order to understand the underlying topology of African NRENs. Traceroute is a network diagnostic tool used to determine end-to-end paths of network packets where round trip times are relayed at each router hop [16] [32][33].

By presenting such information in a visual and interactive manner; gaps, anomalies, clusters or patterns in the data may be identified [6][10][25][47]. Such a visualisation would be useful in identifying possible routes that network traffic traverses between NRENs (continental vs intercontinental), aiding in the peering decision-making process and helping with identifying network and routing issues such as incorrect or suboptimal routing [47].

As location is an important aspect in determining this information, a geospatial visualisation has been identified as being appropriate. In relation to computer networks, a geospatial visualisation is one in, which nodes are represented in respect to physical locations. This differs from non-geospatial visualisations where nodes are independent of physical locations [54].

With this in mind, the following research question has been formulated for the project: can a geospatial visualisation effectively and accurately communicate the network topology of African NRENs, allowing users to identify networks, where they connect and the routes this traffic may traverse?

In this paper, we present the design of a geospatial visualisation, which visualises the network topology of institutions and NRENs in Southern and Eastern Africa using traceroute data collected from the Ripe Atlas platform. The Ripe Atlas platform and Ripe Atlas

probes were used to collect network structure data [3]. Probes are small, USB-powered hardware devices that hosts attach to an Ethernet port on their router via a network cable [3]. These probes were then used to conduct various traceroute measurements from the networks in which they are hosted [3]. Probes selected for this task are hosted in different NRENs in Southern and Eastern Africa. Traceroutes were then sent from the specific probes to chosen destination IP addresses located within African NRENs or related institutions, allowing for logical topology discovery.

We evaluated the effectiveness and accuracy of the visualisation having conducted usability tests and determined its ability to convey physical and logical topology.

2. LITERATURE REVIEW

2.1 Information Visualisation Design

An information visualisation (InfoVis) is the representation of abstract data on an interactive visual interface [25] [42]. It is used to reinforce human cognition and solve problems, even allowing users to answer questions they did not have initially know they had [25] [26][39] [41].

2.1.1 Existing Network Topology Visualisations

In Periakaruppan and Nemeth [1999], GTrace, a “Graphical Traceroute tool”, used to discover routing loops and help decide route implementations was discussed. Using several heuristics, the system determines the location of a node as the traceroute is executed before displaying the traceroute on a world map as series of nodes (hops) and links. A table at the bottom of the screen displays more detailed information about the traceroute including the hop number, hop IP Address and hop host name [39].

In a paper by Munzner et al. [1996], a geographic representation of the Mbone (Internet multicast backbone) was generated such that arcs of lines overlapping a 3D globe represented tunnels that were the end points of the Mbone virtual links. Previously, information on the topology of the Mbone was only available in a textual format and deriving information about the configuration of the network was difficult from the large dataset [34]. Through the creation of this visualisation, problems with configuration (such as inefficient tunnel placements) were identified [34].

In Gilmore et al. [2007], router and Autonomous System (AS) level maps of the African Internet were generated using data collected from traceroutes sent to selected IP addresses. An Autonomous System is a single network or group of networks controlled by a single organization [27]. At the router level, a java-based tool, Terrapix, was specifically created for the study, where 2D and 3D visualisations mapped nodes and links to geographic locations. For the AS level, CAIDA’s Walrus tool was used to generate logical node-link, graph visualisations in a 3D space. Using these visualisations, a “picture” of the African Internet was pieced together - though the accuracy of this is questionable as traceroutes in the paper were only conducted from a single vantage point [45].

2.1.2 Design Guidelines and Frameworks

A practical starting point for information visualisation applications is the use of the Visual Information-Seeking Mantra by Schneiderman [1996]. This consists of the principles of overview (“gain an overview of the entire collection”), zoom (“zoom in on items of interest”), filter (“filter out uninteresting items”) then view details-on-demand (“select an item or group and get details when needed”). Rather than a framework though, Craft & Cairns [2005] has noted that there is a need for the formalisation of the mantra and that a robust methodology should be devised. Despite this,

Schneiderman’s [1996] paper has been heavily cited since publication demonstrating its utility. Yi et al.’s [2007] paper presents similar categories of InfoVis techniques but on a broader spectrum: select (“mark something as interesting”), explore (“show me something else”), reconfigure (“show me a different arrangement”), encode (“show me a different representation”), abstract/elaborate (“show me more or less detail”), filter (“show me something conditionally”) and connect (“show me related items”).

It should be noted that rather than an evaluation method that can be used to assess the effectiveness of a visualisation; design principles simply offer various approaches to design implementation [21].

2.1.3 Representation and Interactivity

The most common way of presenting computer networks is the use of a graph representation, which consists of nodes and edges or links [6][54]. This is unsurprising as the data itself is defined as being a “network” data type in, which items are linked to an arbitrary number of other items and cannot be organised into a tree or hierarchical structure [10][47]. This presents a challenge in visualising such data as there can be both many nodes and many links all of which are connected to each other causing display clutter and occlusion of edges [6]. One way of addressing this issue is by aggregating links or nodes together but Becker et al. [1995] believes that this could obscure important information. This leaves the implementation of interactivity (such as those tasks mentioned in the Section 2.1.1) to solve this problem [6].

As the position of nodes are fixed in geospatial visualisations, interactivity is particularly important in addressing areas where large amounts of clustered points may occur: since nodes cannot be rearranged freely on the display being fixed by location, occlusion of links or nodes is possible. Ellis & Dix’s [2007] paper offers a detailed account of various clutter reduction techniques including those related to appearance (such as sampling and filtering), spatial distortion and use of animations as a temporal technique.

In terms of the representative design of a visualisation, Young and Munro [1998] discuss desirable properties of visualisation representation including individuality of components, distinctive appearance of different representations, high information content with low visual complexity, scalability of visual complexity and information content, flexibility for integration into visualisation and suitability for automation.

Munzner [2008] discusses visual encoding issues related to space (2D vs 3D) and colour such as using appropriate colour scales with distinguishable gradients and catering for those with colour blindness.

2.2 Information Visualisation Evaluation

According to Knight [2001], a visualisation is considered effective if it is suited for the task for which it supports and the representation metaphor is appropriate for the dataset. In order to determine the effectiveness, an evaluation of the visualisation needs to be conducted.

In Hatch et al. [2001], several areas of information visualisation were identified including the (incorrect) use of design guidelines (discussed in section 2.1.2), feature-based evaluation frameworks, scenarios and walkthroughs and user and empirical studies. The limitations of each of these methods is also discussed.

Plaisant [2004] offers some alternative methods to visualisation evaluation mentioning controlled experiments comparing design elements, usability evaluations, controlled experiments comparing two or more tools and case studies of tools in realistic settings.

A prominent issue surrounding information visualisation evaluation relates to the concept of usability and the visualisation itself ie. the distinction between the interface and the visualisation [26]. For example, a visualisation may be deemed effective but the application as a whole (the interface plus the visualisation) may be unusable [26]. This interaction between usability and visualisation makes evaluation difficult and few papers take into account the differences between the two when discussing visualisation evaluation methods.

Other challenges experienced with visualisation evaluation are concerned with the influence of the domain in, which the visualisation is used and a need to look at data over long periods of time and from different perspectives [17][21][26][40].

3. DESIGN AND IMPLEMENTATION

3.1 Approach

The purpose of an information visualisation is to allow users to analyse and evaluate data that is presented in a graphical format [9]. A User-Centred Design (UCD) approach, where the user is involved throughout the design process, ensures that the visualisation produced is appropriate and addresses the users' needs [2] [10][52]. Users of the visualisation are envisaged to be NREN managers and network engineers of related tertiary education institutions of the UbuntuNet Alliance.

The design process consists of three phases: the early envisioning phase, the global specification phase and the detailed specification phase [52].

In the early envisioning phase, requirements gathering is done and an analysis made of the current situation of users in terms of tools, tasks and goals [2][52]. In the context of an information visualisation, this would be gaining an understanding of the initial visual queries (an information need addressed by a visualisation) that potential users may have. Several techniques can be applied to collect this information including background interviews, questionnaires, surveys and focus groups [2].

During the global and detailed specification phase, a solution is proposed and presented to users [2] [52]. Each phase lasts approximately 2-3 weeks where the iterative tasks of analysis, design and evaluation takes place across all phases (Figure 1.) [2][52].

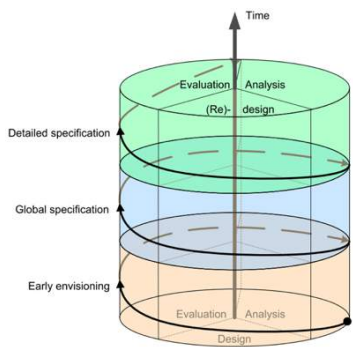


Figure 1. User Centered Design Approach from Wassink et al, 2009.

Before the start of each phase, it is necessary to first analyse users, their tasks and the domain and context in, which they currently perform these tasks [52].

Once analysis has taken place, various solutions can be designed and proposed based on results (user tasks and scenarios) gathered from analysis [52]. These solutions may come in the form of a prototype, whether it be a low fidelity (Lo-Fi) implementation such as a paper prototype or a high fidelity (Hi-Fi) prototype in, which an interactive system is created [52].

After a prototype has been designed and built, it is necessary to evaluate it. This can be done through methods such as focus groups, interviews, questionnaires and usability tests [2][52].

Iteration of the design cycle is concluded once a specific criteria has been reached, such as if users are able to adequately answer visual queries [52].

3.2 Iteration 1: Early envisioning

The early envisioning phase was the first iteration of the User-Centred Design approach used for the creation of the geospatial visualisation. The focus in this phase is on gaining an understanding of potential users, the tasks they perform and the environment in which they perform these tasks [52]. Using this information, user tasks and goals can be formulated to guide future visualisation design and functionality [2] [52].

3.2.1 Analysis and Requirements Gathering

In order to obtain real user tasks and goals, users working within NRENs as network engineers, managers, CEOs and CTOs were contacted. This helped ensure that the design of the visualisation was grounded in the real needs of users even if these participants were not accessible in later iterations of the design cycle.

An online survey and an interview were conducted to try uncover current practices around network management and the type of issues experienced.

The online survey devised enquired about currently used network management operational tools and metrics of interest such as latency and throughput. Specialised individuals working within UbuntuNet Alliance-affiliated NRENs and organisations were sent emails with a link to the survey. Of the responses received, a "lack of comprehensive routing information" was stated as a network management limitation encountered while network down-time and congestion were cited as common network problems experienced.

The interview organised was conducted with a technical specialist from the University of Cape Town's Information and Communication Technology Services (ICTS) department which manages the university's internal network and connection to the Tertiary Education and Research Network of South Africa, TENET. Many of the questions mentioned in the survey were asked in the interview making the interview semi-structured in nature. As the interview progressed, it became evident that the needs and interests of ICTs were more concerned with the university's internal network and that NREN level insight could not be provided without contacting TENET directly.

3.2.2 Implementation

The design of the first prototype of the visualisation was largely based on existing traceroute visualisation tools such as the OpenIPMap prototype [1].

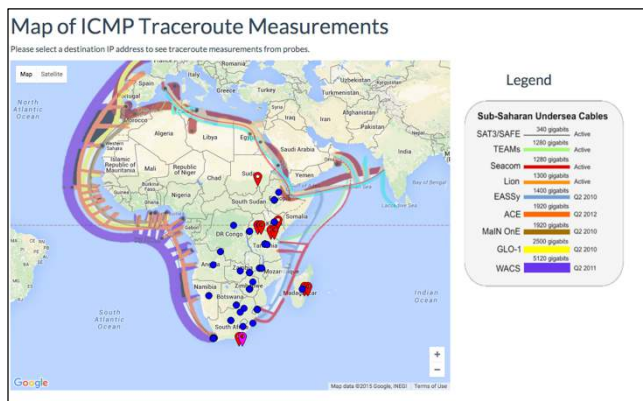


Figure 2. Screenshot of Interactive Visualisation Prototype

An interactive prototype (Figure 2) with limited functionality was produced using the Google Maps Javascript API v3 and a small sample of traceroute data collected from the Ripe Atlas platform. The MaxMind GeoLite City Database was used to map IP addresses to coordinates on a city level and used to position markers on the map for both probes and destination IP addresses [15]. NREN probes were represented with red marker symbols, university probes as purple markers and destination IPs as blue circles. A route was illustrated on the map connecting the probe, hops and destination IP markers as a line with an animated arrow indicating the direction of the traceroute. An image overlay was placed on the map to show the positioning of undersea fibre cables around Africa.

3.2.3 Evaluation

An informal user feedback evaluation was conducted with the expert user group to get feedback on the visualisation. During this session, a brief demo of the visualisation was given. The user group consisted of domain experts in networking from the department of Computer Science: two postgraduate students, two technical staff members and a networks lecturer.

During the evaluation, several expert users raised concerns about the accuracy of the traceroute data collected. These related to both using traceroute as a methodology for topology discovery (different traffic types may be routed along different routes) and the way in which coordinates obtained for IP addresses shown on the map may be incorrect – while an IP address appears to come from Europe, it may actually be located in Africa. Additionally, it was suggested that rather than showing each hop of a traceroute, hops should be aggregated and shown on a country level.

Users had differing opinions on the undersea fibre overlay surrounding Africa: one user thought the multiple lines and colours in the overlay added too much noise to the visualisation and should be removed while another thought it was useful to perhaps reason which cable was taken by the traceroute to the destination.

This prompted the issue of being mindful that some routes shown may make use of satellite links instead of physical links which result in high RTT.

3.3 ITERATION 2: GLOBAL SPECIFICATION

In the global specification phase, solutions are proposed to users and stakeholders [52].

3.3.1 Analysis and Requirements Gathering

Prior to the informal user feedback evaluation (in section 4.3) a focus group was conducted with the same expert user group in the same session. Reasons for why there are such high latencies for source and destinations pairs within Africa was discussed as well as what requirements and additional data would be needed in order to help solve this problem.

Rather than interviewing these users on an individual basis, it was thought that discussion amongst members of the focus group would trigger additional ideas and comments [52]. Given the lack of requirements gathered in the previous iteration, it was imperative that the goals of users be determined.

It was discovered that users were interested in understanding whether high latencies occurred due to a lack of physical infrastructure (fibre cable) or the result of routing protocols that need to be changed. For this reason, a requirement mentioned was that terrestrial fibre for Africa should be shown in order to support the traceroute information already represented by the visualisation.

Other goals extracted from the focus group were allowing for a hop by hop analysis in order to determine where problems might be on a per link basis – this could be illustrated in the visualisation by varying the speed of the arrow animation for every hop jump.

3.3.2 Implementation

Based on the requirements gathered, it was necessary to obtain data concerning terrestrial fibre cable. A source for this information was suggested by a user in the focus group.

Using the freely available geojson files from the AFTerFibre Project (the African Terrestrial Fibre Optic Cable Mapping Project), this information incorporated with the functionality of the previous iteration of the map [46].

It was decided that the undersea cable overlay be removed since it would not be possible to identify exactly whether a certain cable was used for intercontinental routes.

3.3.3 Evaluation

An informal usability test was conducted during this iteration as only minor changes had been made from the previous iteration's prototype [29]. Users who performed the usability test were from the novice user group as this iteration's evaluation focused on evaluating user experience.

Three users were observed as they performed simple tasks using the visualisation. Their reactions, difficulties and emotions were observed as they completed these tasks. At the end of the informal test, users were conversationally interviewed about their likes and dislikes of the visualisation.

3.4 FINAL VISUALISATION DESIGN

Figure 3. shows the final visualisation design based on information received in both the first and second iteration. In addition to the Google Maps Javascript API the DataTable, javascript table plugin for jQuery was used [23].

The location of Internet Exchange Points in Africa was added to the visualisation as an additional dimension of data. This information was obtained from the Internet Exchange Point Directory managed by Packet Clearing House [41]. Only currently active IXPs in Africa were included in the data displayed in the visualisation.

Schneiderman's Visual Information Seeking Mantra (*overview, zoom, filter and details on demand*) was applied when designing the interface and visualisation flow [47]. Users are first presented with

an overview of all the available IP addresses which traceroutes are sent to on a map (Figure 3a). Mousing over an icon displays an info window with information related to that point of interest. After clicking a chosen destination IP address icon on the map, multiple traceroute measurements are shown on the map from all available probes to that particular IP address (Figure 3b). Clicking a selected probe icon, allows the user to view a single, traceroute with detailed hop information being displayed in the adjacent table (Figure 3c). Clicking a row in the table, zooms in on the related icon on the map. Selecting the checkboxes allows different layers (terrestrial fibre, probes, internet exchange points) to be added to or removed from the map. The search box can be used to filter results in the table.

Different symbols were used to represent different types of data on the map: destination IPs are represented by different coloured circles on the map and colour-coded by country so that users (NREN managers) can more easily locate a point of interest (Figure 3a). Probes were shown on the map as blue diamonds, intermediate hops of the traceroute as small green circles and IXPs as pink triangles as seen in Figure 3a. These features differed on two channels of colour and shape to make items distinguishable from each other.

4. FINAL EVALUATION AND RESULTS

4.1 Evaluation Metrics

The evaluation methods conducted were short-term and assessed potential use of the visualisation [29]. Evaluating user experience was necessary in order to understand participants' views of how the visualisation supported intended tasks [29]. Users' subjective feedback and opinions of the visualisation tool were taken into account and used to determine the effectiveness, accuracy and usability of the visualisation [29].

4.1.1 Effectiveness and Accuracy

Effectiveness refers to a tool's functionality and examines a user's performance when performing tasks [8].

Rather than correctness in the data, accuracy refers to the way in which the information is conveyed to the user – that is, can users accomplish tasks in order to obtain the correct answers to a set of questions related to visual queries? Visual queries were associated with user goals and were based on requirements received during the analysis activities of the different UCD iteration phases.

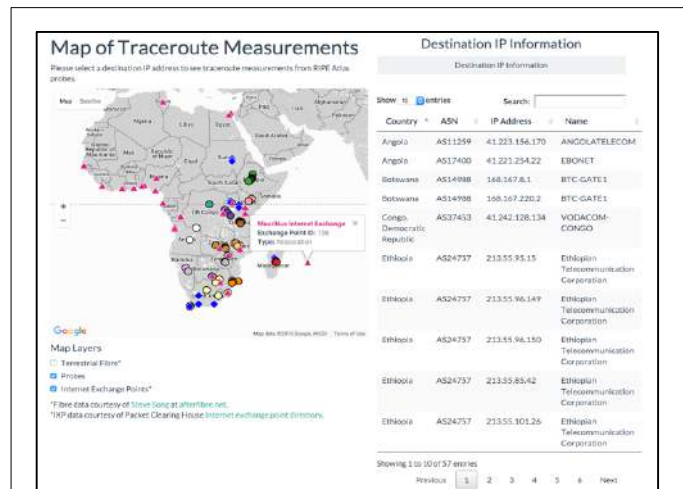
4.1.2 Usability

Usability describes the quality of use of an application by a user (ease of use, satisfaction, efficiency) and is therefore an important aspect of the visualisation to consider [13][52].

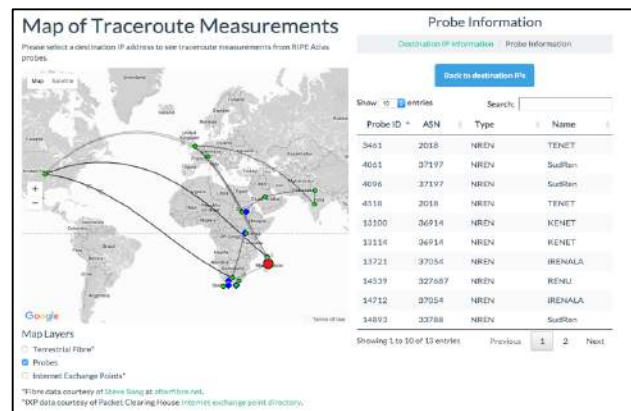
During usability tests, users' interactions with the system were observed as they performed a set of typical, predefined tasks so that performance measurements such as task completion and task success rate were collected [2] [8] [29] [52] [53]. Tasks for the test were based on important features of the system that needed to be tested. Usability tests can help uncover design flaws in prototypes. This allowed for newly discovered problems to be addressed in later design iterations [32] [41][55].

Users' opinions and satisfaction were also gauged during usability testing through use of the System Usability Scale (SUS) [7].

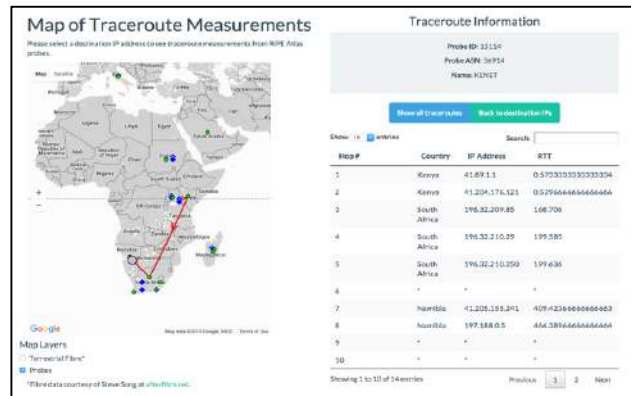
The System Usability Scale is a questionnaire that consists of 10 items where participants rated their responses according to a Likert Scale which ranges from 1 ("Strongly disagree") to 5 ("Strongly agree") [7]. The score for each question is then calculated and a total score obtained out of 100 [7]. SUS measures both learnability



a) Initial overview screen



b) View multiple traceroutes to selected destination IP address



c) View a single traceroute to a selected destination IP address

Figure 3. Screenshots of Final Visualisation Design

and usability of a system; is free to use and is technology independent, being applicable to a broad range of interfaces (web, mobile, etc.) [8] [44]. In addition, the scale has been proven to provide valid results even for small user sample sizes [8][44]. These factors make the SUS an ideal method of evaluation for the project, where access to users was limited.

4.2 Usability Tests

Usability tests were conducted with a total of 23 users to assess the effectiveness, accuracy and usability of the visualisation. Metrics measured during the usability test were successful task completion (to gauge effectiveness and accuracy) and perceived ease of use of the visualisation (to determine usability), through incorporation of the SUS questionnaire, on completion of the question set. The test lasted approximately 30-40 minutes and were conducted in hourly sessions.

Ethical clearance was obtained from the Science Faculty Research Ethics Committee and the Department of Student Affairs. Before taking part in the usability test, participants were asked to sign a consent form informing them of the anonymity of their results. On completion of the usability study, users were compensated for their time with a standard hourly fee as specified by the Department.

Users were split into two user groups. This was done as different users have different tasks and goals and provide different forms of feedback [2] [53]. The first user group consisted of expert users or domain specialists. These are users who are professionals within the field of networking who are most likely to resemble actual users of network managers and network engineers. The second user group consists of novice users who have limited working and conceptual knowledge of computer networks.

Of the 23 participants, all but one user was from the novice user group. Although this user was a postgraduate Computer Science student, due to this user's experience in the networking field, they are considered part of the expert user group. The novice user group consisted of a mixture of fourth year honours and undergraduate Computer Science students from third and second year. Both third year and honours students would have completed a Computer Science module in networks.

Tests were conducted in an uncontrolled environment of the Computer Science honours laboratory. Participants accessed a webpage that contained the visualisation, using either a laboratory computer or personal laptop through a browser of their choice.

As the visualisation required domain knowledge of National Research and Education Networks and traceroutes, it was necessary that documentation explained these concepts. This was provided as pre-reading along with a brief explanation of the visualisation interface.

Users then performed a series of instructed tasks which served as a self-guided walkthrough of the available functionality of the visualisation. This allowed users to familiarise themselves with the interface before they attempted to answer the 10 questions.

Rather than observe users throughout the test process, users were allowed to conduct tasks and answer questions independently within the 30 minutes of the usability test session. The reason for this is that users who are observed will alter their behavior and may become nervous resulting in mistakes and errors affecting results [52]. However, if users experienced particular difficulties in completing a task or found the instructions to be ambiguous, the facilitator could be asked for help or clarification. Where users had problems completing a task, they would be directed to a page with a summary of interactions in the documentation. Most users completed tasks successfully after they reviewed this information.

4.2.1 Task Design and Visual Queries

Tasks for the usability test were designed with two objectives in mind: first, to establish if users could correctly answer visual queries and second, to determine if users could use the interactive

functionality of the visualisation to answer the aforementioned visual queries. Such an approach is based on verifying whether users can reach a goal using an application which implements a visualisation technique [52][54]. The first objective addressed the evaluation aspect of accuracy while the second objective targeted usability.

The visual queries formulated were questions related to identifying networks (physical and logical), where they connect (location of source, destination, intermediate hops) and potential routes of traffic traversal (traceroute paths at a country and continental/intercontinental level) as stated in the research question (Table 1).

Table 1. Mapping of Visual Queries to Research Question Themes

Visual Query	Visual Query Type	Research Question Theme
Which country on the African continent has the most fibre?	Physical Network: Most Fibre Cable	Network topology; identification of physical network
What is the route for the traceroute between institution A and institution B?	Route of Traceroute: Country level	Identification of potential routes of traffic traversal; where networks connect (source, destination and intermediate hops)
Does the route for a traceroute from institution A to institution B travel intracontinentally (within the continent)?	Route of Traceroute: Intracontinental Level	Identification of potential routes of traffic traversal; where networks connect (source, destination and intermediate hops)
Does the route for a traceroute from institution A to institution B travel intercontinentally (to a different continent)?	Route of Traceroute: Intercontinental Level	Identification of potential routes of traffic traversal; where networks connect (source, destination and intermediate hops)

Ten questions were formulated for the usability test - four based on answering the visual queries mentioned in Table 1 and six composite tasks which gauged the successful completion of a combination of high-level subtasks of *overview*, *zoom*, *filter*, *details on demand*, *relate*, *history* and *extract* as described by Schneiderman [1996]. That being said, these six tasks can essentially be classified as *locate* tasks when applying Valiati et al.'s [2006] taxonomy of tasks. *Locate* tasks are defined as those related to searching and finding information already visualized, identified or determined on the display [51].

4.2.2 System Usability Scale Questionnaire

On completion of the list of questions, users were asked to fill in a System Usability Score questionnaire to determine the usability of the visualisation [7]. While the scale provides a measure of usability, it cannot be used to reason why users provided certain scores - that is, it cannot be used to diagnose usability problems [43].

As a result, free-response questions were added to the questionnaire to evaluate user experience along with usability. These consisted of

a field for “General Comments” (where users’ reactions, opinions and problems encountered could be described), “What features were useful?” (to determine commonly used features) and “What features are missing?” (to elicit overlooked requirements) [32].

4.3 Analysis of Results

4.3.1 Visual Query Accuracy and Task Completion

Successful task completion is characterised by the ability of a participant to obtain specific data when carrying out a task [37][51]. If a question was answered correctly by a participant in the question set, then the task was deemed to have been successfully completed. This same definition applied to the accuracy of answering visual queries. As users were not observed individually during usability tests, reasons behind certain results can only be hypothesized based on users’ responses.

Results showed that participants were able to view the physical topology in the visualisation and based on the representation used, correctly determine the country with the most fibre cables with 100% accuracy (Figure 4). Visual queries related to routes were answered with less accuracy: identification of a traceroute’s route on a country level had 72.73% accuracy; 68.18% accuracy on an intracontinental (within the continent) level and intercontinental (between continents) level.

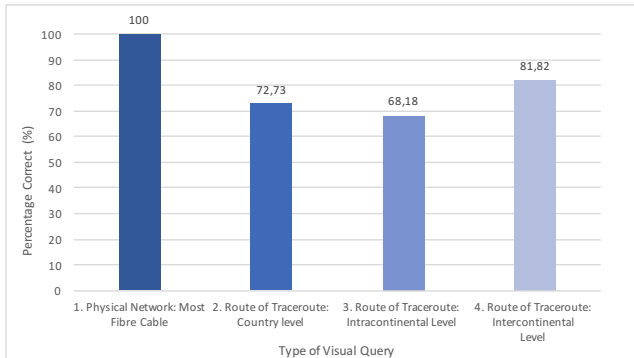


Figure 4. Correct Visual Queries Answered

When examining the results of Visual Query 2 in Figure 4, of the 6 participants that answered this question incorrectly, 2 participants had comparable answers mentioning similar countries. On further investigation, it was inferred that rather than using the traceroute information provided in the table, these users had made use of the map to determine the traceroute path. The errors are therefore explainable in that there is a distortion between model and reality in the map representation: while a traceroute in its entirety is represented as a line drawn over several countries, it is only the hops in those countries that indicate the actual route taken by the traceroute. This indicates that some users have difficulty in reconciling a physical location with a logical link - although a lack of domain knowledge may also have contributed to this mistake. This further indicates a weakness in the visualisation where there is a lack of awareness in the correlation between the the map (model) and reality, as presented in the table of contextual information.

An explanation for diminished accuracy for identifying traceroutes with intracontinental routes vs intercontinental routes is less determinable (Visual Query 3 and Visual Query 4 in Figure 4). It is possible that the wording of the questions may have been a source of confusion when using “intracontinental” and “intercontinental” though these terms were clarified as being either “within the continent” or “to a different continent” respectively. Furthermore, it is possible that these questions might not have been sufficiently clear enough for participants to gauge the type of answer required:

two participants responded to these questions with, “no”, “North America” and “both”. While these responses in context of the questions may be valid conceptually, they have been excluded from being classified as correct within the results.

Providing answers to questions in multiple-choice would help to resolve the problem of ambiguity in answers such as those aforementioned [51].

Figure 5 shows the percentage of the six tasks successfully or partially completed during the usability test.

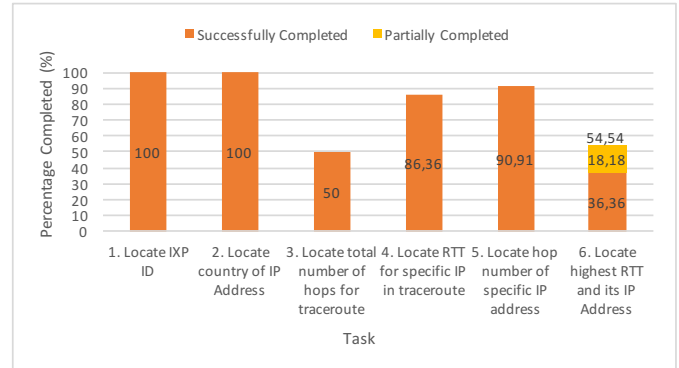


Figure 5. Successful Tasks Completed

Both Task 1 (locating the ID of an IXP) and Task 2 (locating the country of a particular IP address) had 100% successful task completion. In comparison to these tasks, Tasks 3,4,5 and 6 had lower successful task completion rates. This is understandable though as Tasks 3,4,5 and 6 were tasks that required more complex subtasks to be performed thus increasing the the likelihood of an error.

Of the more complex tasks, Task 3 had the lowest successful completion rate with only half the participants (50%) having obtained the right answer. After analysing the results, three possible reasons were identified for why this may be. The most common possible reason (6 out of the 11 participants who answered incorrectly) is that when viewing the traceroute information in the table, the table shows a default limit of 10 hops on the webpage at once thus prompting users to assume that only 10 hops were taken to the destination. This assumption was made despite pagination buttons and a label indicating the total number of entries in the table - albeit these were located at the bottom of the table. Users may therefore not immediately notice these indicators (especially on smaller screens where users have to scroll down the webpage), resulting in errors. Having pagination and table entries displayed more prominently at the top of the table may help resolve this issue. The second reason hypothesized for cause in error, is once again a mismatch between the model presented by the map and the reality of the data: hops indicated on the map are aggregated, as several hop IP addresses may occur in the same, single location. Thus while it appears on the map that a traceroute may have taken only 5 hops to reach a destination, the reality is that 19 hops were taken and represented in the information table. The last reason theorized is as the icons for the specified IP address is situated close to the icon of another IP address, it is possible that the incorrect destination IP was clicked showing the wrong results.

For Tasks 4 and 5, only 3 participants and 2 participants respectively answered these questions incorrectly (with one participant having not answered the questions at all). Without having observed these users on an individual basis, it cannot be reasoned why they were not able to complete the tasks successfully.

In Task 6, users were required to locate both the highest RTT and the IP address which had this highest RTT value for a particular traceroute. This resulted in several responses where users failed to read the second part of the question and only responded with the highest RTT. This demonstrates an error in the question design and can be resolved by either breaking down the question into different question items or having only one part of the question asked. As this was an error in the question design, if a user was able to correctly identify the highest RTT, this was included in the results and marked as partially completed (Figure 4). After examining users' responses, it was noticed that all users who incorrectly identified the highest hop number in task 3, all had the same incorrect answer for the highest RTT. This is understandable in that it indicates that users looked at the currently displayed list of results in the table and would not have navigated to the next section of results of the table, which had the correct highest RTT.

The success rate of all 10 questions (4 visual queries and 6 tasks) across all participants was calculated to be 79.55% where successfully completed tasks (correctly answered questions) were allocated 1 point and partially answered questions were allocated 0.5 points [37].

According to Sauro [2011] who conducted an analysis of 1200 usability tasks, the average task-completion rate is 78%, which means the task completion rate for the visualisation is above average. When estimating this figure as a percentile, it was calculated that a task-completion rate of 79.55% is better than 55.4% of all tasks, which were a part of the 1200 tasks analysed [43].

At a confidence level of 95%, the confidence interval was calculated to be between 0.7371 and 0.8437 meaning between 73% and 84% of all potential users will be able to complete the tasks successfully [43][44].

4.3.2 System Usability Scale Scores

Each participants' score from the System Usability Scale questionnaire was calculated: odd numbered questions are calculated as the user's response on the scale minus one while even numbered questions are scored as five minus the user's rating [7]. These two figures are then added together and multiplied by 2.5 to obtain a figure out of 100 [7].

Figure 6 presents the frequency of System Usability Scores by category for 23 users who participated in the usability test and a pilot usability test by an expert user. The scores shown are for a total of 24 participants.

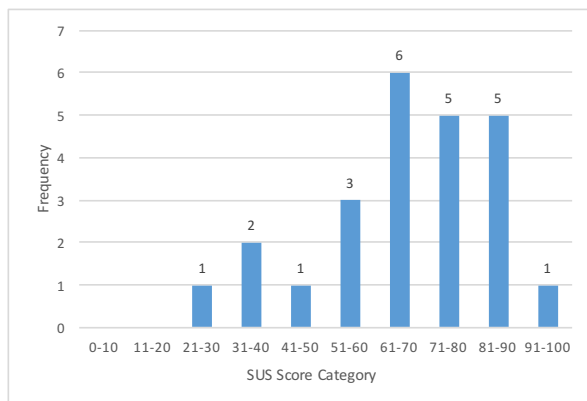


Figure 6. Frequency of individual SUS scores by category.

The average SUS score was then calculated to be an average of 67.82.

In an analysis of 500 studies making use of the SUS, the average score was 68 [44]. Thus, the visualisation falls just below the average score - 12 out of a total of 24 respondents scored the visualisation greater than the average of 68.

That being said, this does not mean that the system is below average in terms of usability. When analysing this score on the adjective rating scale in Figure 7, it falls between "Ok" and "Good" though more towards the threshold of "Good" [4]. Further analysis on the acceptability range in Figure 6 places the SUS figure for the visualisation at a "marginal high", which is just below the "acceptable" range [4].

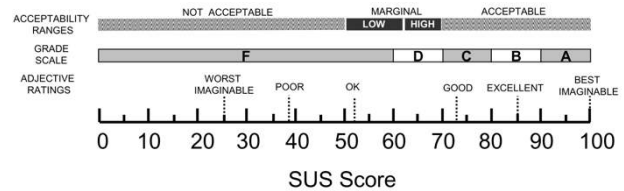


Figure 7. Comparison of different scales in relation to SUS Score from Bangor et al., 2009.

According to Bangor et al. [2008], systems with SUS scores less than 70 should be further examined for improvement indicating that there are still usability issues that need to be considered in the visualisation. That being said, it is likely that only minor changes will need to be made as the visualisation is just below the "acceptable" margin on the acceptability range scale.

4.3.3 User Experience Feedback

Additional free-response questions were appended to the System Usability Scale questionnaire to more adequately determine what usability problems participants experienced during the test and to gauge their user experience.

These questions were: "General comments", "What features were useful?" and "What features were missing?". It was not compulsory for users to fill in these fields.

Thematic analysis was used to analyse the results on a per question field basis [9]. In thematic analysis, themes are sensed by first reviewing the data (text) and then coding the text [9]. Coding is process of subdividing and labeling data to creating encodings [9]. An open-coding process was used where themes and codes were derived directly from the text itself [9].

Only explicit themes were extracted from the data as the wording in some user's feedback was ambiguous or difficult to interpret. Additionally, due to the small sample size, only themes with more than one occurrence were considered.

The themes extracted from "General Comments" are presented in Figure 8. As users could mention any aspect of the visualisation, it was necessary to group comments by broader, overarching concepts such as those related to usability problems or learnability.

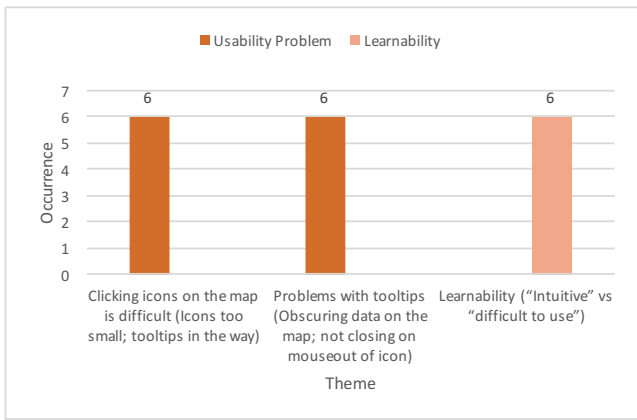


Figure 8. Theme Analysis of responses to “General Comments”

From Figure 8, it can be seen that both clicking icons on the map and problems experienced with tooltips were usability problems that affected users’ experience of the system with an equal number of occurrences. Issues around learnability also proved to be a theme that users identified but ranged in sentiment: some comments mentioned that the system was “intuitive” or “easy after some time using it” while others stated that it was “hard to use”.

Themes extracted from the question “What features were useful?” are displayed in Figure 9.

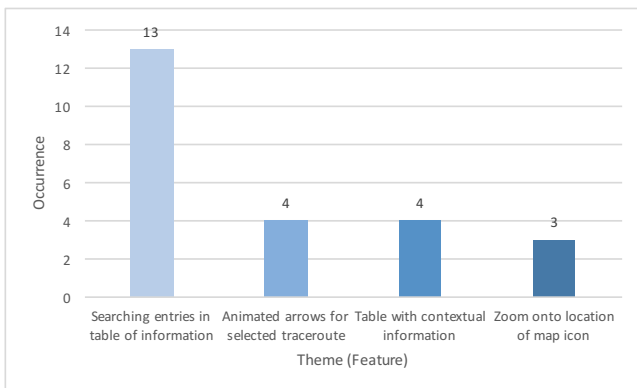


Figure 9. Theme Analysis of responses to “What features were useful?”

From Figure 9, it can be seen that the search functionality of the table was the most cited useful feature, with a considerable difference in frequency mention in comparison to other features (animated arrows for selected traceroute; table with contextual information; zoom onto location of map icon), which were only marginally different to one another.

Given the nature of the question set, which contained mostly *locate* tasks, it is understandable how users identified “search” as an important and useful feature.

Extracting themes for “What features were missing?” were more difficult than the previous two questions as half the respondents either did not fill in this field (as it was optional) or answered that they did not think any features were missing or could not think of additional features.

The themes that were identified are shown in Figure 10 and were consistent in occurrence across different themes.

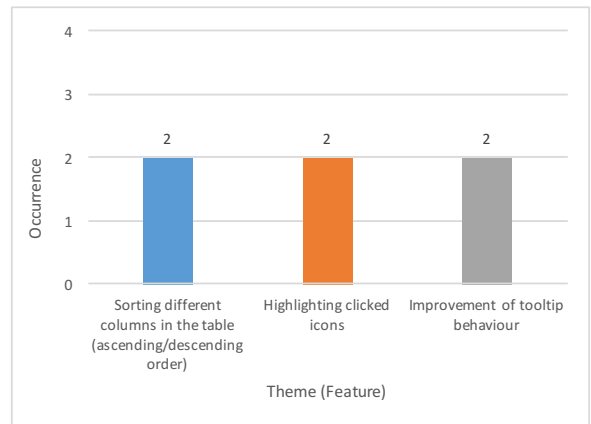


Figure 10. Theme Analysis of responses to “What features were missing?”

After conducting theme analysis across all three responses, usability issues were extracted from these themes. These originated from the “General Comments” section and “What features were missing?” responses and can be used as a starting point for the next design cycle phase and future implementation. For instance, applying Human Computer Interaction (HCI) concepts such as Fitt’s Law to the issue of difficulty in clicking map icons may help solve this problems. Fitt’s Law states that the time it takes to acquire a target is a function of the ratio of the distance and width of the target, meaning that if a target is larger, it is easier to click.

5. LIMITATIONS

5.1 Data and Visualisation Representation

Data Usability describes the quality and reliability of data used for information visualisations. As data structure allows assumptions to be made about the type and amount of data expected as input for the visualisation, it follows that there may be a distortion between model and reality [13][26][42]. Therefore, it is necessary to understand the issues surrounding the use of traceroute as a method for topology discovery as limitations of the dataset will inevitably be reflected in the visualisation [13][26].

Firstly, there is the issue of accuracy of the data: due to firewalls, load-balanced routers and multi-protocol label switching (MPLS), various traceroute methods (ICMP, UDP, TCP) may have less accurate results [16] [33]. This could result in an incomplete view of the visualised network structure. That being said, alternative traceroute methods (such as Paris traceroute) have been devised to address the aforementioned problems allowing for a more complete network structure to be obtained.

In addition, it has been shown that different traceroute methods yield different topologies, where ICMP-based traceroutes reach more destinations collecting a greater number of AS links while UDP-based methods reach less destinations but infer a greater number of IP links [30].

In terms of the visualisation, a mismatch between the model and reality was uncovered during the usability tests where the reality represented by the visualisation (eg. number of hops, traceroute links joining hops) was not an accurate reflection of certain aspects of the data. This is due to the limitations of the dataset in terms of the accuracy of geolocation coordinates for IP addresses when using the Maxmind GeoLite Cities database. As the database maps IP addresses at a city level, it is possible that different hop IP addresses may resolve to the same coordinates. While the table on the right hand side of the visualisation presents more detailed hop

information of actual traceroute data, it may be necessary to indicate the number of hops in a single location on the map visualisation in order to ensure consistency between the visualisation and the traceroute data presented in the table. This way, if one adds up the numbers for each hop in a location on the map, this will match the number of hops in the table.

Another way to ensure consistency between the map and the table may be to have a column in the table with the city rather than the country name.

5.2 Usability Testing

5.2.1 Participants

Making use of a User-Centered Design approach means that access to potential or intended users is imperative. These users need to not only have the appropriate domain knowledge and be easily accessible but also be available throughout the design cycle to ensure consistent feedback. Sourcing such users was challenging as not only are they highly specialized in their role (and therefore few) but also geographically dispersed.

Participants of the usability test were mostly novice users meaning that only simple interactions and visual queries of the visualisation could be evaluated and not those related to data analysis and reasoning due to lack of domain knowledge. A limitation of making use of novice users is that such users may not have a clear understanding of the problem the visualisation is trying to solve (ie. the decision making process of placing IXPs) or insight into the data (understanding of traceroutes) [17][40]. Having expert users participate in future usability tests would help address these issues.

Furthermore, as participants were representative users, it is possible that the goals of real users (network managers and engineers working within African NRENs) may not have been addressed.

5.2.2 Environment

Usability tests were conducted in an uncontrolled environment in the Computer Science honours laboratory where other students were present. This means that participants of the usability study could have been distracted by the activities of those around them leading to errors when completing tasks.

6. CONCLUSIONS AND FUTURE WORK

In this paper, we presented the design of a geospatial visualisation of the network topology of National Research and Education Networks in Africa using traceroute data. A user centered design approach was used and applied over two iterations. The final visualisation was designed as a culmination of these two iterations. The visualisation shows various dimensions of data on the map including the location of Internet Exchange Points, the placement of terrestrial fibre and traceroute information. In comparison to other traceroute visualisation tools (such as GTrace and Terrapix mentioned in Section 2.1.1) which either only visualise a single traceroute measurement or display tracoutes from a single vantage point, multiple traceroutes sent from various vantage points can be viewed on the map.

In the final evaluation, we investigated whether the geospatial visualisation designed can effectively and accurately communicate the network topology of African NRENs and allow users to identify networks, where they connect and the routes this traffic possibly traverses. Effectiveness and accuracy were evaluated by checking the correctness of the visual queries answered. These visual queries related to the identification of networks (physical and logical), the location of the source, destination and intermediate hops of these

networks and potential routes of traffic traversal at a country and continental level. It was demonstrated that the visualisation was able to effectively and accurately communicate the country with the most physical network infrastructure in Africa without error and that the logical topology and potential routes of traffic traversal could be identified at a country and continental level with an accuracy of over 60%. This figure of 60% applies to identifying where networks connect in terms of source, destination and intermediate hops as together, this information forms a route.

The effectiveness and accuracy of where networks connect and network traffic routes could be improved by making specific information (pagination and number of entries within the table of information) more visible to users and making them aware of the caveats presented by the visualisation (such as the inaccuracy of the map in comparison to the table in terms of hop count) or by implementing improvements to the visualisation (indicating the number of hops aggregated in a single location).

Usability tests revealed that the system was considered marginally usable and that with some improvement could be classified as acceptable after addressing issues raised by users. Another usability test could then be conducted to verify if these changes improved the SUS score of the system. Once issues of usability have been addressed, a further evaluation would then need to be conducted with expert users to determine whether the visualisation supports decision making with regard to the placement of IXPs; allows inferences to be made about which links make use of satellites and where routing problems might be. An investigation into the field of traffic engineering may also reveal more feature requirements such as allowing users to view and compare different traceroute protocols (ICMP, UDP, TCP). This would be useful in that different traceroute protocols yield different topologies, showing routes the different types of traffic may take.

Avenues for future work would be to integrate the Ripe Atlas data and visualisation into a single extensible software platform. A database would be used to store the data and both historical and user-uploaded data could then be visualized.

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