Exploring Flow Metrics in Dense Geographical Networks

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Abstract: We present FLOWMATRIX, a system for the interactive exploration of time-labeled multivariate flows between pairs of geographic locations. FLOWMATRIX offers a coordinated visualization based on the interplay between a geographic map and a matrix that allow to discover trends tied to specific locations while offering an overview of metrics of the flows between all pairs of locations. The input data is clustered following a geographic hierarchy and the user can navigate between different levels of detail. The design of our system privileges the execution of simple tasks like assessing the volume and features of the flows between pairs of locations, enumerating destinations with poor performance, and sorting flow streams based on their volume.

1 INTRODUCTION

The research presented in this paper is the result of a collaboration between a research group focused on information visualization and a big player in VoIP telecommunications that needs to assess and monitor the traffic load and the quality of service (QoS) offered to its customers. In particular, the company is interested in understanding the relationship among the volume of traffic, the QoS, and the geolocation of the components of its infrastructure.

Logs of exchanges of traffic *flows* are collected in the order of millions of records per day. Such data is intended to be used for ex-post analysis, supporting different levels of detail, as the company is truly distributed worldwide. Also, since the data sets are huge, the user should be able to filter them at least with respect to the geography, the specific time interval of interest, and the different performance metrics available. Finally, since communication flows are inherently directional, the user should be allowed to perceive the relationship between the quality of the communication and its direction.

The main challenges lie in the density of the networks under examination, in the need of binding the information to a geographic map, and in the requirement of looking at data at different abstraction levels. On top of that, the input data becomes more interesting when it is put in a historical perspective and enriched with many different facets and key indicators.

In our paper we present a system aimed at facing the above challenges. It is called FLOWMATRIX and it is designed for the interactive exploration of time-labeled multivariate flows between pairs of geographic locations. FLOWMATRIX offers a coordinated visualization based on the interplay between a geographic map and a square matrix that allow to discover trends tied to specific locations while offering a general overview of metrics of the flows between all pairs of locations.

The paper is organized as follows. Section 2 contains a detailed analysis of user requirements. In Section 3 we describe our contribution and in Section 4 we provide some details on its implementation. We then proceed to describe our use cases in Section 5, followed by the results of an evaluation study we conducted with domain experts (Section 6). Section 7 explores the state of the art and finally, our conclusions are in Section 8.

2 REQUIREMENT ANALYSIS

Our reference data set is composed of a collection of data cases, each representing a single message transmission from a source to a destination, that are both labeled with their geographic location. Such an exchange is equipped with a timestamp and a set of quantitative attributes describing the quality or quantity of exchange (e.g. packet loss, bandwidth).

Several data cases can be grouped together, either by time or by geography of source and destination, into a *flow* where the original quantitative attributes are naturally aggregated (summed up or averaged depending on the context).

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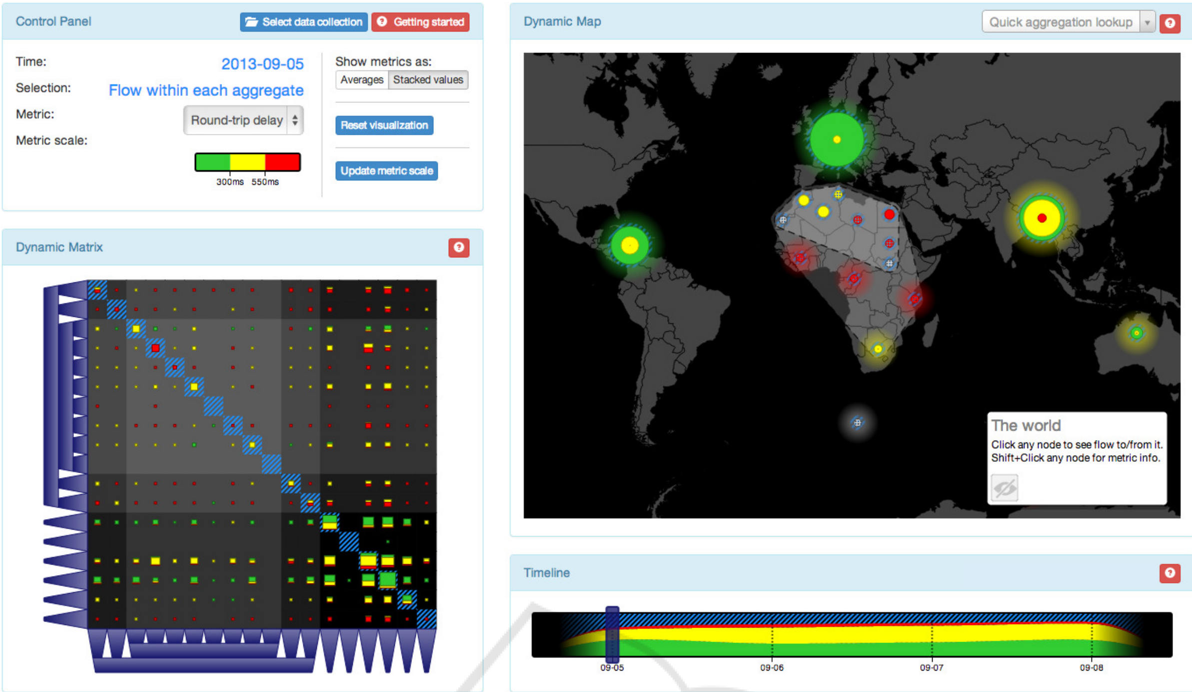


Figure 1: Overview of the interface of FLOWMATRIX.

Informal interviews with the domain experts originated the following restricted set of requirements, that were refined through several iterations.

R1: Assessment of quantity and quality of flows. The interface should convey to the user both the quantity of flows and their quality in terms of performance indicators. For example, the user may want to immediately discover if a major event, as the deployment of a software update, impacted the performance of the infrastructure.

R2: Choice of the aggregation level. Users should be able to cluster the geographic locations that constitute the domain of the source and destination in the data cases. Such clustering should be performed at arbitrary levels of detail, i.e. starting from fine-grained locations and scaling up to macro-regions of the world, according to well-known administrative, political, and geographical boundaries.

R3: Time-oriended exploration. The user should be allowed to explore the data focusing on the events of a specific time instant and, hence, assessing the quantity and quality measures for contemporary flows. For example, that is the case for ad-hoc analysis triggered by specific events like network failures.

R4: Performance-oriended exploration. The system should allow the user to focus on performance thresholds with the aim of discovering periods when such thresholds have been violated by some flow. Also, it should be possible to discover in what time intervals the flows have different qualities with respect to the average scenario.

3 DESIGN OF THE INTERFACE

In this section we introduce FLOWMATRIX. We first describe its interface and its interaction primitives and then we proceed with a discussion of our design choices.

3.1 Interface and Interaction

The interface of FLOWMATRIX is presented in Fig. 1. It is split into four main parts: the control panel (upper left corner), the timeline (lower right corner), the dynamic matrix (lower left corner), and the dynamic map (upper right corner). In the following description we consider a sample data set with two quantitative attributes, i.e., round-trip delay and packet loss between pairs of geographic locations, typical of the domain of computer networks and telecommunications.

The *control panel* contains basic information on the current state of the visualization and a small set of controls to change the selection and representation of quantitative attributes. From the control panel in Fig. 1 we can infer that the focus is on a specific day (5 Sept 2013) and we are looking at the flow "within each aggregate", i.e., having both source and target locations within any of the geographic clusters in the current view (e.g. flows within Europe, within Americas, etc). The selected quantitative attribute is the round-trip delay measured between pairs of locations. The three colors used in the other views (green, yellow, red) identify three different classes of values for each quantitative attribute, reported in the metric scale that is visible just below the name of the attribute. In the example in Fig. 1 green means "below 300ms", yellow means "between 300ms and 550ms", and red means "above 550ms". The right side of the control panel contains additional buttons. The user can choose between two different types of representation for quantitative attributes: 1. *averages*, i.e., only one average value for each flow between a pair of geographic clusters; or 2. *stacked values*, i.e., the weighted distribution of attribute values in the three different classes detailed previously, identified with the corresponding colors. The two threshold values in the metric scale that give rise to the different classes of values can be dynamically adjusted by clicking the appropriate button in the control panel (requirements R1, R4). Finally, a button allows the user to bring the visualization back to the original state (before any interaction).

The *timeline* contains a graph with aggregate information for each aggregate value in the time scale chosen by the user. More specifically, three stacked ribbons show the volume of flow over time for each of the three classes of metric values, as defined in the control panel. When the mouse pointer is placed over the graph, additional information for the selected time interval is shown on screen. The user can either drag the slider or directly click the timeline to change the time selection. The interface is updated accordingly to show the corresponding data (requirement R3).

The *dynamic matrix* shows attribute classes for all possible pairs of geographic clusters in the current view, based on the selection on the timeline. More specifically, it is a square matrix, where rows and columns respectively represent sources and destinations of flows. Each cell in the matrix represents the flow between a pair of geographic clusters, with size logarithmically proportional to the total volume of flow and colors reflecting the values of the quantitative attribute in the current representation (requirement R1). The trapezoids on the left and bottom sides of the matrix represent the set of visible geographic clusters and all their ancestors. The cluster hierarchy is explicitly represented by means of side contact between parents and children; see Fig. 3 for an example where the hierarchy is expanded from the continent level to the country level (requirement R2). Such technique is a simple variation of common algorithms for tree representation (see, e.g., (Schulz, 2011) for a detailed survey). All matrix elements are left intentionally unlabeled, so that the user can focus on discovering patterns and trends in the data by looking exclusively at the color and size of each cell. Hovering any element with the mouse reveals aggregate information for the corresponding entity. In particular, trapezoids yield information about the geographic clusters they represent, while cells in the matrix yield information on the flow between the two involved clusters.

The *dynamic map* shows a circle for each geographic cluster in the current view, positioned at the centroid of the corresponding locations on the map. At any time, each of such circles shows the same volume and metric values as one of the cells in the matrix. The dynamic map, therefore, only shows a linear subset of the information contained in the dynamic matrix. Such portion can change based on user interaction. In the initial state circles in the map are in correspondence with cells on the diagonal of the matrix, i.e., each of them represents the flows for which source and destination are both within the corresponding geographic cluster. The regions with dashed borders that enclose groups of circles represent the same hierarchy of clusters that is pictured with trapezoids in the dynamic matrix. The information panel at the bottom right corner shows appropriate information depending on user interaction. The user can also hover individual circles and dashed regions to get the volume of flow and quantitative information on the selected attribute.

We designed our framework with a focus on interactivity and responsiveness. The main operations that the user can perform are the following: 1. *geographic view change*, i.e., updating the set of visible geographic clusters, by either exploring the children of a geographic cluster or collapsing sibling clusters into their parent cluster (requirement R2); 2. *geographic cluster selection*, i.e., narrowing the analysis to the flow originating from a geographic cluster, targeted at a geographic cluster, or between two geographic clusters (requirements R2); 3. *time selection*, i.e., selecting the appropriate time aggregate on the timeline to see corresponding values (requirement R3); and 4. *attribute class customization*, i.e., tweaking the two threshold values that determine the three different classes of attributes identified by three colors: green, yellow, and red (requirement R4). The first two operations can be achieved by interacting indifferently with the dynamic matrix, the dynamic map, or a combination of both. Upon user interaction, all the components in the interface are automatically updated to reflect the new state of the visualization. The reader can refer to Section 5 for a high-level description of use cases that prove how to exploit our system in real-world scenarios.

3.2 Discussion of Design Choices

The interface has two main components, i.e., the dynamic matrix and the dynamic map. If the user is interested in looking up flows for specific geographic locations, the dynamic map offers the quickest alternative. The search box can be used if the exact location of a country is not known in advance. On the other hand, the dynamic matrix is entirely focused on the quantitative attributes, and its regular structure makes it possible to spot events affecting specific sources or destinations of flow.

Regarding requirements listed in Section 2, we observe that the interface of FLOWMATRIX addresses them as follows. An overview of the quantitative attributes in the data set (requirement R1) is offered by the sizes and colors of cells in the matrix. The geographic clustering (requirement R2) can be leveraged both in the matrix and in the map by means of intuitive user interaction (i.e. double-click with the mouse). Filtering the flow based on source and destination or switching between incoming and outgoing flow (requirement R1) can be achieved by clicking the appropriate geographic clusters (clicking on an already selected cluster reverses the direction of the flow). The timeline allows for a quick selection of time (requirement R3) by means of simple mouse clicks, and offers an overview of the historical context with the stacked ribbons. The performance indicators can be easily customized by changing the thresholds through the control panel (requirement R4).

Regarding the absolute scaling of the circles on the map, we are aware of the potential perceptual problems described in Flannery's work (Flannery, 1971). However, we observe that the user tasks typically involve estimating the maximum and the minimum circle area rather than the ratio between specific pairs. Also, the contemporary presence of the corresponding stacked bars in the matrix tends to compensate for perception errors.

FLOWMATRIX makes use of animation in two different occasions: 1. in response to user interaction, the smooth transition to the new state of the interface is realized with a simple animation; and 2. to represent the direction of the flow on the map, concentric circles are pictured as either emanating from or collapsing on the selected circle. We specifically refrained from using animation to convey crucial information (e.g. historical trends in the data set), following the guidelines and caveats found in recent literature (see, e.g., (Robertson et al., 2008; Di Donato et al., 2016)).

4 IMPLEMENTATION

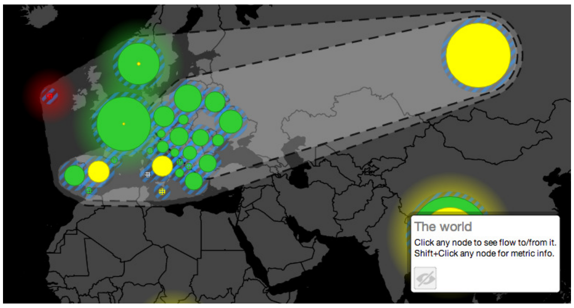
The algorithmic background of FLOWMATRIX is pretty straightforward. The drawing of circles in the dynamic map is achieved with an iterative force-directed graph layout algorithm (Di Battista et al., 1999). Each circle is represented with two nodes connected by one edge: the first node is fixed at the ideal position for the center of the circle, i.e. the centroid of the corresponding geographic cluster, while the second is subject to forces and represents the actual position of the visualized circle. The edges connecting such pairs of nodes are modeled as zero-length springs. Since each node is attracted to its ideal position there is no need to introduce repulsive forces between nodes. However, in order to avoid overlap among visualized circles, a simple collision detection heuristic is introduced that adjusts the relative positions of two nodes in case a potential overlap is detected. The areas with dashed borders that enclose circles in the dynamic map are obtained with a state-of-the-art algorithm (Rappaport, 1992) for the computation of convex hulls of circles. We use the same algorithm to compute a clipping path for the representation of flow "waves" between any pair of geographic clusters (see, e.g., Fig. 2(b)).

FLOWMATRIX is a Web application implemented in JavaScript, using the popular D3.js framework (Bostock et al., 2011) for the development of highly interactive data-driven visualizations. All the components of the interface are coordinated following the Publish-Subscribe pattern, so that any user interaction is transformed into an event that triggers appropriate updates in each component. We made a special effort to improve the performance of the tool, limiting animations and redraws where possible. That is crucial especially in the dynamic matrix, where the number of cells grows quadratically upon expansion of geographic clusters.

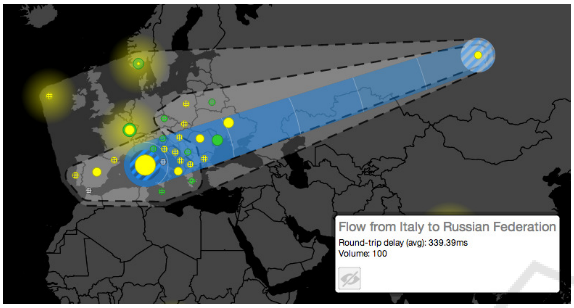
5 USE CASES

In order to show the effectiveness of our approach, in this section, by means of four use cases, we describe how simple and complex tasks can be achieved by taking advantage of the coordinated view of FLOWMATRIX.

Use Case 1: *Finding the total volume of flow and the average round-trip delay from Italy to Russia on*



(a)



(b)

Figure 2: Sequence of user interactions needed to study the flow from Italy to Russia. (a) The dynamic map is zoomed on Europe, where two sub-regions (Southern and Eastern Europe) are expanded to reveal their respective countries. The size of each circle is proportional to the volume of flow within the corresponding country. (b) The dynamic map is focused on the flow from Italy to Russia.

8 Sept 2013. First of all, we select the correct date on the timeline and choose to visualize only average values for quantitative attributes using the appropriate button on the control panel. We then locate the circle that represents Europe on the dynamic map and double-click it. The interaction has the effect of updating the geographic view by adding all the subregions within Europe to the current representation. The dynamic map and the dynamic matrix are updated accordingly, making room for the new clusters. We repeat the same step with the two circles representing Southern Europe and Eastern Europe, with the effect of enriching the view with all associated countries, including Russia and Italy. The state of the map reached after the initial interaction is in Fig. 2(a). Note that the circles representing European countries lack the semi-transparent "glow" effect, meaning that they cannot be further expanded to reveal more detailed information (i.e., we reached leaves in the cluster hierarchy). Note also that the smaller circles are filled with a grid-like pattern, meaning that their flow volume would be too small for a proportional representation on the map, and therefore their radius is adjusted to an acceptable minimum length. We click the circle representing Italy, triggering the following

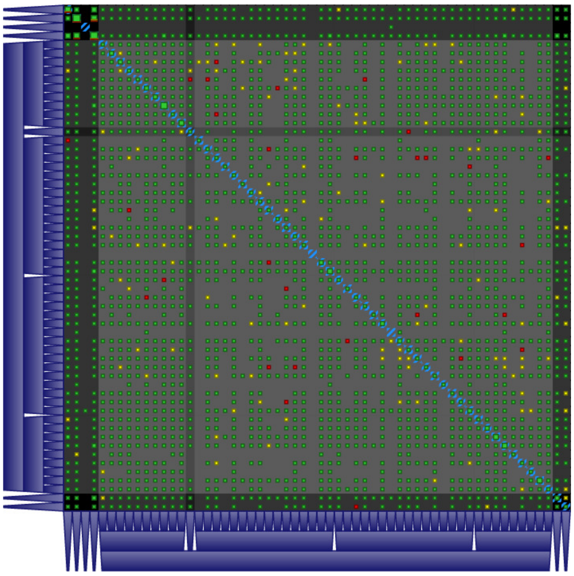
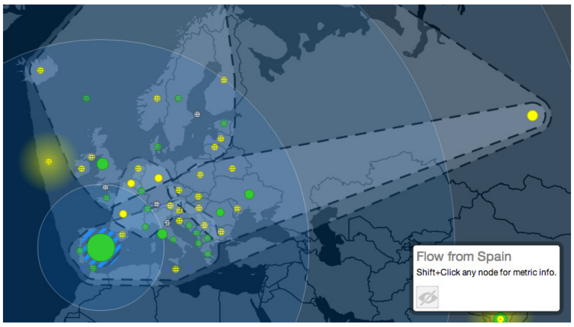


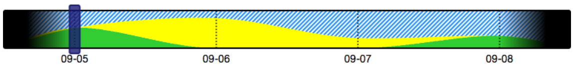
Figure 3: Dynamic matrix showing country pairs with average packet loss greater than 10% in red.

updates: 1. the row representing the flow from Italy in the dynamic matrix is highlighted; 2. the size and color of each circle in the dynamic map represents the flow from Italy to the corresponding geographic cluster, and the flow itself is pictured with animated concentric waves emanating from the clicked circle; 3. the stacked ribbons in the timeline show aggregate data for the flow from Italy to all other destinations. We can achieve the same result by looking up the selected country in the search box positioned at the upper right corner of the dynamic map (visible in Fig. 1). Finally, we hold the Shift key and click the circle representing Russia. New updates are triggered: 1. the square in the dynamic matrix representing the flow from Italy to Russia is highlighted; 2. the flow in the dynamic map is represented with waves from Italy to Russia, as shown in Fig. 2(b); 3. the stacked ribbons in the timeline show aggregate data for the flow from Italy to Russia. The requested information can be found in the info panel on the dynamic map.

Use Case 2: *Counting how many country pairs in Europe have average packet loss greater than 10% on 6 Sept 2013.* This task shows the potential of the dynamic matrix when analyzing a data set which grows quadratically with respect to the number of geographic clusters. First of all we focus on the control panel, choosing the right quantitative attribute and updating the range of values such that flows with packet loss greater than 10% are identified with the red color. We select the right date on the timeline and the appropriate metric on the control panel. We then focus on the dynamic map, first double-clicking the circle



(a)



(b)

Figure 4: Views showing details for the third use case. (a) The flow from Spain is pictured with concentric blue circles. The size of each circle is proportional to the volume of flow from Spain to the corresponding country. (b) The stacked graph in the timeline reaches its peak on 6 Sept 2013.

representing Europe and then all the circles representing sub-regions in Europe, until we reach the country level. We can finally focus on the dynamic matrix and simply count all the occurrences of red cells that fall within the portion of matrix related to European countries, as visible in Fig. 3. Although small, their color is enough to get a quick overview and answer the original question.

Use Case 3: *Finding out what European country receives the highest volume of flow from Spain on 5 Sept 2013 and which day sees the highest volume of flow between the same pair of countries.* We select the right date on the timeline. Since we focus on the volume, the visualized quantitative attribute is irrelevant. We focus on the dynamic map to show circles for all European countries and click the circle representing Spain. Apart from Spain itself, the biggest circle in Europe is the one representing United Kingdom, as visible in Fig. 4(a). That is an effective and sufficient visual clue to understand that United Kingdom receives the highest percentage of flow from Spain. To answer the second part of the question we hold the Shift key, click the cluster representing United Kingdom, and focus on the timeline (see Fig. 4(b)). The day with the highest volume of flow from Spain to United Kingdom is 6 Sept 2013.

Use Case 4: *Studying how a firmware update recently rolled out on the hardware equipment impacted performance and reliability*. Suppose that the deployment involves hundreds of thousands of hardware components all over the world, and is conducted incrementally in one week starting from Asia, continuing with Europe, and ending with the entire globe. In preparation for the analysis, we compile a data set based on logs collected by the different components of the infrastructure. The three numeric attributes that are included in each data case are the following: round-trip delay, packet loss, and the percentage, called π, of traversed hardware components with the most recent firmware version. The data is aggregated on a daily basis and spans the entire week spent in the deployment of the new firmware.

First of all, we select π as the metric to visualize from the control panel, and tweaks the thresholds for the value classes so that transmissions with $\pi = 100\%$ are green, those with $50\% \leq \pi < 100\%$ are yellow, and the remaining are red.

During the first two days in the selected week, we observe the expected steep increase of green flow within Asia by clicking and Shift-clicking the related circle on the map and looking at the colors on the timeline. We also expect a corresponding increase of yellow flows between Asia and other continents, in particular Europe and Oceania, given their geographical proximity that implies a higher percentage of traversed hardware components residing in Asia. Assume that, after clicking the circle representing Asia on the map, we find out that the circle for Europe, representing flow from Asia to Europe, stays mostly red during the two-day interval. To inspect the causes of this, we move to the dynamic map and expand both Asia and Europe to reveal the corresponding subregions. Suppose the circle representing flow within Middle East stands out for its red color. This would immediately prompt us to click it and see whether outgoing and incoming flows are also mostly red. We would conclude that the deployment in Middle East was slower than expected, which probably also impacted the flows between Europe and Asia, given the strategic location. A further expansion of the Middle East cluster on the map may confirm that most of those countries have red values for π.

We can proceed to explore data for the following two days to confirm that the flows within Europe and those between Europe and Asia progressively turn green, while Europe's incoming and outgoing flows turn yellow.

As a next step, we could shift our attention to the measured performance of flows. We first change the visualized attribute to round-trip delay, focus on the same geographic clusters and flows mentioned above, to observe whether any suspect variation of performance values occurred during the deployment phase. Suppose we observe, when switching to the packet loss attribute, a noticeable degradation of performance (i.e. an increase of average values) that follows the same temporal and geographic patterns of the deployment studied before. We would therefore be induced to conjecture a suspected correlation and look for unnoticed bugs in the latest firmware update.

Finally, we can verify if the deployment is complete at the end of the week by selecting the π attribute, clicking the last date on the timeline and focusing on the dynamic matrix. Suppose two cells in the matrix are still partially red and that they correspond to the flows in both directions between Africa and the Americas. We can expand both clusters on the map and discover, for example, that the problem can be narrowed to the flows between Northern Africa and the United States, concluding that there is a specific portion of the infrastructure, involving only the two areas, for which the deployment is not yet complete.

6 EVALUATION

FLOWMATRIX was conceived with the goal of allowing users to get quick insights on data sets detailing flows between geographic regions. Since any interaction with the tool can be decomposed into recurring tasks, it becomes crucial to verify that these can be correctly and quickly accomplished by prospective users. This section presents the results of the evaluation study we conducted after implementing our prototype.

We initially thought of conducting a comparative study, where participants would need to solve a list of tasks both with our framework and with standard tools (e.g. database queries). However, we quickly discarded this option because even the expert users we interacted with did not have experience with a standard, unified set of tools for the purpose of accessing and analyzing the same data set. Therefore any comparison would have suffered from potential bias, depending on the relative experience of the participant. We opted instead for a qualitative study, where participants were given a set of tasks and feedback was collected at the end of each task.

6.1 Study Design

In preparation for the study we fed our prototype with a precomputed data set, structured like the one used for the figures in Section 3 and containing data for four days between 5 Sept 2013 and 8 Sept 2013. The study was conducted with ten participants (nine male, one female) all aged between 25 and 35 years old. They are all domain experts with a background in computer science, statistics, telecommunications, or electronics. At the time of the study, they were already familiar with the data collection from which we derived the data set used as input for the evaluation. More than half of the participants had worked with the same data collection before, accessing its content by means of database queries or simple time series plots.

Each participant was initially tested for color blindness. A thorough introduction to the framework followed, with a focus on each of the views and all the available user interaction. A couple of example tasks were illustrated step by step. After that, each participant was asked to solve 15 tasks. The first four were treated as training tasks, i.e., the participant had the possibility to ask for help. For each task the examiner recorded the completion time with a stopwatch, gathered feedback at the end of the execution, and showed a quicker way to achieve the same result in case the strategy adopted by the participant was clearly suboptimal. General feedback was asked from each participant as a final step after the last task. The average time required by each participant to complete the study was 50 minutes.

6.2 Results and Discussion

All the participants successfully completed the proposed tasks, adopting different strategies based on the context. The statistics on task completion times are reported in Table 1. It is evident that users quickly learned from mistakes done in previous tasks. For example, 60% of participants had an instinctive preference for the dynamic matrix when solving Task #13, i.e., they updated the set of expanded geographic clusters and compared the size of different squares without using the dynamic map. After being shown a faster solution that makes a better use of the dynamic map, they quickly changed their strategy and performed much better with Task #14 and Task #15. This is confirmed by the relatively small standard deviation for the completion time of both tasks, which suggests that users knew precisely what steps where needed to complete them. Note also how the median completion time is smaller than the average time for most of the tasks, which suggests that the outliers can be interpreted as occasional difficulties or distractions experienced by individual users.

The feedback was overall very positive and enthusiastic. All participants were particularly impressed by the possibility to finally “see” the data they had only been able to access with database queries and simple two-dimensional charts. They also appreciated the power of exploring data both on the dynamic map and the dynamic matrix at the same time, depending on the specific task. Many important suggestions for

Table 1: List of tasks and results of our qualitative study. For each task the average (*avg*), median (*med*) and standard deviation (*stdev*) values for completion times are listed.

#	Task	Time (s)		
		avg	*med*	*stdev*
1	Find volume of flow from Africa to Europe on 7 Sept 2013	17.2	15.5	9.13
2	Enumerate regions receiving flow from Africa with average round-trip delay greater than 550ms on 6 Sept 2013	42.9	41.5	17.06
3	Enumerate pairs of regions that have more than 50% of flow with round-trip delay greater than 700ms on 6 Sept 2013	90.3	96.5	37.29
4	Enumerate continents that receive flow from Belgium on 5 Sept 2013 with average packet loss smaller than 1.2%	82.2	72.5	27.52
5	Find volume of flow from Portugal to Spain on 5 Sept 2013	34.2	30	13.25
6	Find average round-trip delay from Portugal to Spain on 7 Sept 2013	39	33.5	20.66
7	Find day with highest volume of flow from Portugal to Spain	27	21	15.23
8	Find which region receiving flow from Americas has highest percentage of flow with packet loss higher than 2% on 5 Sept 2013	54	52	12.21
9	Find pairs of regions with average round-trip delay greater than 700ms on 5 Sept 2013	35.9	34	13.31
10	Find pairs of regions with more than 50% of flow with round-trip delay greater than 700ms on 5 Sept 2013	26	25.5	7.94
11	Find days in which the average round-trip delay within Italy is greater than 300ms	49.7	45	14.07
12	Find days in which the average round-trip delay from Italy to Russia is between 320ms and 330ms	58.6	52.5	16.63
13	Find the European country receiving the highest volume of flow from Spain on 6 Sept 2013	124.5	112	45.06
14	Find the European country receiving the highest volume of flow from Northern Africa on 5 Sept 2013	46.7	50	8.54
15	Find how many European country pairs have average round-trip time greater than 1s on 5 Sept 2013	59.6	57	14.13

improvement were collected during the study. 80% of participants found the timeline to be not enough intuitive to compare the volume of flow between different days, and suggested to add an explicit indication of the total volume of flow. 50% would have appreciated the possibility to expand geographic clusters straight to the finest level of aggregation, without intermediate levels, i.e., sub-regions. 50% had trouble to come up with the right sequence of interactions to highlight the flow within a specific geographic clusters on the dynamic map (i.e., click followed by Shift-click on the same circle). 50% initially overlooked smaller squares in the dynamic matrix, while 20% suggested to add a "full-screen" capability to the dynamic map and the dynamic matrix as a solution. 50% spent a non negligible amount of time wondering where to find the actual answer for some tasks, after completing all the right interactions. 40% suggested to add a smarter search box to programmatically specify a query in the form "flow from A to B". 40% complained that the size of circles in the dynamic map is not a sufficient clue to estimate the volume, although they succeeded in their tasks after comparing the actual volumes for the bigger circles (in the range of 2 to 4). Further minor observations were related to the specific data set (e.g. 40% were not sure whether Russia was to be found under Europe or Asia) and to the lack of experience with the interface (e.g. 70% of users needed some time before appreciating the distinction between average and stacked metric values).

7 RELATED WORK

The solution we propose to explore flows is a coordinated multiple view featuring both a map and a matrix. Hence, we survey the related research areas and compare with the solutions proposed for similar problems.

7.1 Thematic Maps

Visualization of abstract data on maps, is a traditional topic in cartography, where choropleth maps, proportional symbols maps, dotted maps, etc are used to visualize the distribution of statistical variables. Although the non-geographic data represented in such thematic maps is usually very simple, in some cases it may have a more complex structure. Wood *et al.* (Wood et al., 2010) divide the geographical space with a grid and draw in each cell a replica of the original map that shows inbound flow from all the other regions. Their approach is further expanded in (Wood et al., 2011), where replicas show approximate flow patterns by means of time series plots. Enriching thematic maps with small multiples, however, can lead to cluttered views when the input data set grows in size.

7.2 Visualizing Flows and Movement

There is a rich scientific literature about flows in maps where the trajectory of bodies plays a crucial role. A limited list of applications include the visualization of vessel traffic (see, e.g., (Willems et al., 2009; Scheepens et al., 2011; Scheepens et al., 2012)) and the visualization of aircraft routes (see, e.g., (Hurter et al., 2009; Bottger et al., 2014)). In our data set, however, information regarding the trajectories is missing.

Buchin *et al.* (Buchin et al., 2011) build flow maps using spiral trees to induce a clustering on the targets and smoothly bundle lines. In a more recent work (Nocaj and Brandes, 2013) similar maps are obtained with a new edge bundling technique that avoids ambiguous connections between pairs of vertices. Both techniques are visually compelling when describing the flow from a single source to many targets, but are not adequate for dense graphs.

Andrienko *et al.* (Andrienko et al., 2008) present a taxonomy of the possible approaches available for the geovisualization of dynamics, movement, and change. They identify three alternatives: 1. direct depiction of data, which can easily lead to clutter and slow rendering; 2. use of summaries like aggregation, generalization and sampling; and 3. use of statistical methods to extract patterns before visualizing them. Our approach follows the second alternative, hence addressing requirement R2. Guo (Guo, 2009) proposes an interface to render large spatial interaction data, consisting of multiple views: a geographical map with arrows representing flow between regions, a self-organizing map, and a parallel coordinate plot. The tool is based on a precomputed hierarchical regionalization based on the volume of flow between pairs of regions. Although reasonable, such regionalization does not support the type of clustering imposed by requirement R2.

7.3 Matrix-based Coordinated Views

Elmqvist *et al.* (Elmqvist et al., 2008) present a matrix visualization technique that features fast reordering of rows and columns, data aggregation with explicit representation, and GPU acceleration to optimize the rendering on screen. Their approach inspired part of our work while constructing a dynamic matrix optimized for pattern recognition. In particular, while the matrix representation has been effectively coupled with a node-link representation in (Henry and Fekete, 2006; Henry et al., 2007), we couple it with a geographic visualization to represent flows among geolocated sites, where the matrix provides an aggregatable view of all-pairs relationships while the geographic map shows the sources and destinations of the flows the user is interested in.

A visualization problem very similar to the one described in this paper is addressed by Boyandin *et al.* (Boyandin et al., 2011), who propose FLOWSTRATES, a visualization framework in which the origins and the destinations of the flows are displayed on two separate maps, and the changes of flow magnitudes over time are represented in a matrix-like heatmap in the middle. Hence, although FLOWSTRATES also uses a matrix-based coordinated view, it devotes the expressiveness of the matrix to the temporal evolution of the flows, using one column for each period of time. Each row of FLOWSTRATES matrix represents the evolution over time of a specific flow, the color of each cell being proportional to the amount of flow. Flows that are (on average) bigger than others are placed on the top rows. In order to identify the source and destination of each flow, two leaders, one exiting the leftmost cell and the other exiting the rightmost one, point to the source and the destination locations on the maps, respectively.

With respect to our visualization tool, FLOWSTRATES addresses a simpler visualization problem where flows do not have performance metrics associated with them. Hence, requirements R1 and R4 cannot be met by the proposed techniques. Additionally, FLOWSTRATES' matrix does not support aggregation or clustering of rows and an overall view of the whole data set is not possible (requirement R2). Instead, FLOWSTRATES allows the user to aggregate sources and destinations on the maps with a lazo selection. Although this proves to be a flexible tool, well-known geographic aggregations are not immediate to select and at most one aggregation at a time is allowed in each map.

8 CONCLUSION

We have presented a framework for the interactive exploration of the flow between pairs of geographic locations. It allows researchers, engineers and managers to quickly assess the nature and evolution of flows between pairs of geographical locations at various levels of detail, while keeping an eye on the general picture.

In the future we will extend the set of features of our prototype, overcoming its current limitations. First of all we will follow the suggestions that came out of the qualitative study presented in Section 6. Further, we will extend the representation of metrics, including the display of non-quantitative metrics, the explicit rendering of the distribution of values for each metric, and the possibility to filter specific value ranges for a cleaner visualization. The user will have the possibility to pick pairs of dates on the timeline, in order to compare related metric values looking for potential drops or improvements in performance.

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