ABSTRACT
Several techniques have been proposed to analyze and visualize static network data, but the visualization of dynamic network data is an emerging research field, with several open questions. The dynamic and multi-relational nature of this data poses the challenge of understanding both its topological structure and how it changes over time. In this doctoral proposal, I delineate my plans to investigate how a visual analytics approach, integrating visual, interactive, and automatic methods, can support the examination of dynamic networks. I present the design and implementation of a research prototype, whose effectiveness and usability will be evaluated by experts’ assessments and user studies in a real-world test bed.

KEYWORDS: Dynamic layout, graph drawing, interaction, social network analysis, information visualization, visual analytics.

INDEX TERMS: H.5.m [Information Systems]: Information Interfaces And Presentation (e.g., HCI) – Miscellaneous, I.3.6 [Computing Methodologies]: Computer Graphics – Methodology and Techniques, J.5 [Computer Applications]: Social and Behavioral Sciences.

1 RESEARCH PROBLEM
Dynamic social networks are social networks that take into account changes over time. They not only model relations between human beings in terms of some sort of interpersonal interaction, but also consider the evolution of these relations, i.e. the way and the extent by which they change over time [4]. Dynamic social networks can be useful to model and analyze human relationships in several scenarios. In general they are large, multi-modal, multiplex, probabilistic and temporal. They are large because they have a high number of vertices, a high edge density, and a complex topology. They are multiplex, because more than one edge is allowed for each pair of vertices, and also multi-relational, being these edges of different types. They are multimodal, since there are also different types of nodes. They are probabilistic, taking into account inherent uncertainty or noise in the data acquisition process. They are, lastly, temporal, since they change over time: in the simplest model, the structure of the network is invariant, while the value of attributes associated to vertices and edges may vary; in a more complex model, also the topology itself can undergo changes over time (nodes are fixed, but edges can appear and disappear); in the most complex model, even nodes can appear and disappear over time.

2 STATE OF THE ART
Since the first sociogram was introduced in 1934 [20], several methods have been proposed for visualizing static social networks. The interactive visualization of dynamic networks and its integration with analytical methods and interactive visualizations is an emerging research field.

2.1 Static networks
If we disregard at first the dynamics and consider the problem of visualizing static networks, we find several visualization techniques proposed in Graph Drawing [7], Information Visualization [18], and Data Mining [6] communities. While the usual way to draw a network on a two-dimensional surface is a node-link diagram, we may also draw a network using a matrix-based representation, which seems to be more effective for large graphs but makes it harder to find a path between two nodes [17]. Besides the choice of a model for the visual representation, a layout model is needed. Pure network data, indeed, are not provided with any a priori criterion to determine the geometric properties defined for a given representation. With reference to node-link diagrams, several proposed criteria can drive the optimization of the graph layout in order to enhance the perception, amongst which we can mention: minimizing edge crossing, preserving symmetry, minimizing edge bends, minimizing edge length; all these criteria are referred to as aesthetics [5]. Since the position is a prominent visual variable, a ‘good layout’ not only has to enhance perception, but also has to maximize the conveyed information. On this purpose spring-embedder algorithms, for instance, join the compliance to the aesthetics criteria with a physical metaphor, by modeling nodes as repulsing particles and links as elastic springs [16].

2.2 Dynamic networks
Once we have explored different possibilities for the network representation and for the layout, it is worth to notice that the issue of visualizing network dynamics is not solved by obtaining a temporal sequence of static images. We need to obtain a sequence of dynamic layouts that facilitates the perception of changes, by taking into account additional criteria, such as: preserving orthogonality, proximity and topology; ensuring repeatability, comparability and stability; preserving planarity; preserving edge directions; preserving position and distances; restricting adjustments to small parts. In a general sense, a good dynamic layout must preserve the user’s mental map [10]; in other words, it must minimize unnecessary changes while emphasizing temporal trends or patterns. This causes a conflict between two opposite needs: on the one hand, each layout in the sequence must comply with the aesthetics criteria and must be consistent with the metaphor on which it is based and with its meaning; on the other hand, all the layouts must preserve the mental map. Authors have proposed different automatic methods to set the balance between stability and consistency [21]. Furthermore, empirical studies have shown that the preservation of the mental map is not important in every circumstance and that the extent of this preservation depends on the data and the task [24], and presumably on the user, too.
The aforementioned criteria have led to the development of several dynamic layout techniques, which we can group mainly in two families: offline and online algorithms. Offline algorithms need the entire sequence of temporal graphs, which are aggregated into a compound graph; then an overall or ‘foresighted’ layout is computed as a base for obtaining stable layouts [8]. Online algorithms can compute a dynamic layout in an incremental fashion, by taking into account only previous time-slices [15]. Moody at al. [19] provide a common conceptual framework for both approaches: the dynamic stability is ensured by binding nodes to anchors, which can be random or fixed positions or the position of the nodes in the aggregated layout or the position of the nodes in the previous time-slice.

Given the sequence of dynamic, an important issue for dynamic networks is the visual encoding of the temporal dimension. At least four different approaches exist: mapping time to time, i.e. animation [14]; mapping time to a visual variable, i.e. a superimposition view, in which different time points are distinguished by color or transparency [3]; mapping time to a space axis, i.e. a juxtaposition view, in which the diagrams are displaced side-by-side [1]; and mapping time to a space dimension, i.e. a two-and-a-half-dimensional view, in which two-dimensional graphs are arranged in a stacked pile [9].

2.3 Analytics

Analytical methods usually employed for social network analysis are based on models, metrics, and algorithms of Graph Theory [25]. Common metrics, for instance, are different kinds of node centralities, which determine the relative importance of a given node on the base of its connection to other nodes; popular algorithms are those for finding communities, i.e. node clusters with dense connections within them and sparse connections between them. The integration of analytical methods into an interactive visualization can support the comprehension of relational and temporal aspects of dynamic networks. A common approach is to compute some static SNA metrics associated to node and edges and then encoding them to any visual variable [23]. These metrics can also be used to perform dynamic filtering and some form of multidimensional data reduction, also combining visualization and exploratory data analysis techniques [22]. Besides metrics associated to nodes and edges, analytical methods can compute overall metrics and thus provide synthetic descriptions of the entire network at given instants or intervals; such synthetic descriptions can enable a coarse/grained visual comparison of a large number of networks [13].

3 Research Questions

Considering the stated problem and the related literature, I have formulated one main research question and three sub questions.

Main question:
• How can a visual analytics approach support the examination of dynamic networks according to specific user tasks?

Sub questions:
• How can temporal aspects of network data and dynamic underlying phenomena be best visualized?
• How can we integrate analytical methods and visualization techniques to address the complexity of dynamic networks?
• Is it possible to combine analytical methods and interaction techniques to enhance the perception of network dynamics?

4 Methodology and Research Plan

The first step of my research plan is a state-of-the-art report about network visualization. I investigated which existing visualization techniques can be applied and how they relate to the several aspects of complexity of dynamic networks (temporality, probability, multiplexity, multi-modality, topological complexity). With specific regard to the visualization of dynamics, I explored diverse visualization techniques and identified both differences and common underlying criteria. I also explored existing interaction techniques and their taxonomies, and considered their extension to dynamic networks (e.g., if and how hierarchical clustering can be used in a dynamic context). I have been conducting my doctoral work within the context of a broader interdisciplinary research project addressing enterprise organizational networks, for which I collaborate with a team of experts in methods and algorithms for network analysis, organizational structures, usability engineering and process modeling, both from the academic and the corporate world.

Results from user task analysis conducted by other team members served as a base on which we jointly collected and analyzed the requirements for our application on enterprise organizational networks. Then, based on these requirements analysis and on the state of the art, I have designed and implemented the interactive visualization. In the same way, other members of our team have performed a scouting of analytical methods; developing new methods or improve existing ones is out of our scope, but I exploited and integrated selected analytical methods into visualizations according to Visual Analytics concept. Paradigms from user-centered design and usability engineering have been continuously accompanying design and development: in a first stage, heuristic assessments have been performed on mock-ups and first prototypes to evaluate the understandability of visualization and the usability of interfaces.

As for testing datasets, at first we used network data publicly available in the online social networks and reality mining domains; in the meanwhile, organizational experts out of our team have been collecting real data from an organization, which we have used in subsequent phases. The research prototype will be then integrated in the IT environment of our industrial partner, which provides enterprise-consulting services in the field of process modeling. This will offer a real-world test bed to evaluate the effectiveness of proposed visualizations. Short iterative development/evaluation cycles should ensure the seamless integration of feedbacks.

5 Progress to Date

Besides the analysis of the state of the art and the preliminary experts’ interview to gather requirements, the main milestone I
have accomplished to date is the design and implementation of a prototype [12] and a first cycle of evaluation with experts.

5.1 Design and Prototypical Implementation

Animation is a popular approach to deal with the temporal dimension, but some of the experts interviewed in the requirements survey pointed out that it might interfere with a detailed exploration and might also hamper the comparison between different time-slices, which can be performed only in the user’s memory, harder. Focusing on changes over time, I decided to explore alternative views and to combine them, which is sketched in Fig.1 and explained in the following sections.

5.1.1 Juxtaposition view

By placing node-link diagrams of different time-slices side by side, we obtain a juxtaposition view (Fig. 1.b). This view applies the principle of small multiples and allows the reader to compare the time-slices and find commonalities and differences. Coordinated zooming & panning and coordinated highlighting further facilitate comparison.

5.1.2 Superimposition view

With reference to screen occupancy, we can attain a better performance by superimposing the diagrams (Fig. 1.a). In this case, a visual variable must be employed to differentiate between time-slices. I used transparency, so that more recent elements are more opaque. At first only nodes are shown to reduce occlusion and visual clutter, but edges can be displayed on demand.

5.1.3 Two-and-a-half-dimensional view

Mapping time to an additional spatial dimension results in a two-and-a-half-dimensional view (Figures 1.c and 2). In such a view, I draw diagrams for each time-slice on separate transparent planes, stacked along the horizontal time axis. It combines some of the advantages of the two aforementioned views. Moreover, the added spatial dimension offers us the opportunity to include additional information within this view, as described in the following. 3D zooming, rotating and panning controls allow the user to set the best viewpoint.

5.1.4 Smooth transitions between views

When exploring a complex network, the user might happen to switch repeatedly between views, to find the best suited one for her/his data and task. Therefore, I wanted to preserve the user’s mental map and provide a common context for the interactive exploration of the three views. In order to do so, I designed an interaction metaphor and developed a set of smooth animated transitions between views (Fig. 1). Diagrams are stacked upon each other in the superimposition, then translated alongside the time axis in the juxtaposition view, and finally rotated by 90 degrees around their vertical axes in the two-and-a-half-dimensional view.

5.1.5 Dynamic user-controlled layout

As for the layout, I adopted a continuously running force-directed layout, computed by the Barnes-Hut algorithm [2]. The preservation of the mental map is assured by a mechanism similar to the one used in [11], but in my implementation the user can interactively control the stability-consistency trade-off: a simple slider in the Graphical User Interface (GUI) allows her/him to select stability or consistency and to pass from one to the other through stepwise transitions.

5.1.6 Integration of analytical methods

I considered classical Social Networks Analysis metrics for static (i.e. non-temporal) and single-relational networks, and integrated their computation within our prototype. In this way the user can interactively select a certain SNA metric to be computed for a certain type of relation s/he is interested in; the entire temporal multi-relational network is partitioned into as many static single-relational networks as time-slices are and the requested metric is computed for each of them. Then the resulting values are encoded to visual variables within the visualization (color, size, etc.) for each time-slice; in Fig.2, for example, the eigenvector centrality is mapped to node color.

5.1.7 Interaction techniques

Beside the dynamic layout, with its user-controlled stability, I have integrated additional interaction techniques to facilitate the exploration of dynamic networks: a specific interaction technique to highlight a given node and its connections; and the on-demand visualization of node trajectories by which users can focus on specific nodes and track their evolution. In the two-and-a-half-dimensional view, for example, trajectories run along the spatial dimension dedicated to time (Fig. 2). Shading different colors along the trajectory of a given node shows how its values for a certain metric vary over time. In this way, the results of analytics methods are integrated directly into the main visualization of the network, enabling the user to examine its relational and temporal aspects simultaneously without any additional diagram.

5.2 Evaluation

In the early stages of prototype implementation, I participated in designing mock-ups and formulating tasks for an eye-tracking study, performed with other team members in order to evaluate the effectiveness of our design choices. Although the final aim of our project is to unlock the complexity of dynamic networks to non-expert users, as a first step I performed a qualitative
evaluation with 6 leading experts in network science, from both academia and consulting companies, showing them the prototype and collecting their feedback by the means of a semi-structured interviews, whose results are still under analysis.

6  NEXT STEPS

Further work comprises first of all completing the experts’ evaluation and revising the prototype according to its results. Then we plan to perform a task-based evaluation with a small group of non-experts users, for which I will prepare specific data and tasks; we plan to shape it as a qualitative longitudinal study, accompanying the next design/development iterations. In these forthcoming iterations I plan to carry out some improvements and extensions: exploring alternative representations besides node-link diagrams; further integrating visual and analytical methods, also by passing from static metrics and algorithms to dynamic ones; improving the GUI. Besides providing a continuous feedback for driving the iterative refinement of the prototype, the studies with both experts and non-expert users will be useful to validate the proposed approach and to assess the final outcome of my research work. By combining the lesson learned during design and development with the results of evaluations, I aim to answer my research questions.

7  CONCLUSION

Dynamic networks are very complex objects, because of their time-varying nature and several other aspects. In my doctoral project, which I outlined in this paper, I plan to investigate how we can best integrate visual, interactive and automated methods to address their complexity, also taking into account basic perceptual principles. By designing, developing and evaluating a prototype based on this visual analytics approach, I intend to provide my little contribute to the scientific progress in this area.

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