HAL open science

Exploring Dynamic Multilayer Graphs for Digital Humanities

Stefan Bornhofen, Marten Düring

▶ **To cite this version:**

Stefan Bornhofen, Marten Düring. Exploring Dynamic Multilayer Graphs for Digital Humanities. 10th Conference on Network Modeling and Analysis, MARAMI, Nov 2019, Dijon, France. hal-03019514

HAL Id: hal-03019514

https://hal.science/hal-03019514v1

Submitted on 23 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Noname manuscript No.
(will be inserted by the editor)

Exploring Dynamic Multilayer Graphs for Digital Humanities

Stefan Bornhofen · Marten Düring

Received: date / Accepted: date

Abstract The paper presents Intergraph, a graph-based visual analytics platform for the exploration and study of content in Digital Humanities document collections. The designed prototype is motivated by a practical use case on a corpus of circa 15.000 digitized resources about European integration since 1945. The corpus allowed generating a dynamic multilayer network which represents different kinds of named entities appearing and co-appearing in the collections. To our knowledge, Intergraph is one of the first interactive tools to visualize dynamic multilayer graphs for content in digital collections. Graph visualization and interaction methods have been designed for users without a strong background in network science, and to compensate for common flaws with the annotation of named entities. Users work with a structured and understandable amount of currently relevant data by interacting with a scene of small graphs which can be added, altered and compared. This allows an interest-driven navigation in the corpus and the discovery of the interconnections of its entities across time.

Keywords Visual analytics · network visualization · dynamic multilayer networks · digital humanities

1 Introduction

In recent years vast amounts of the human cultural records have been digitized, further described with metadata and made available in form of collections. To-

Stefan Bornhofen
École internationale des sciences du traitement de l'information
Tel.: +33 1 34 25 10 21
E-mail: sb@eisti.fr

Marten Düring
Luxembourg Centre for Contemporary and Digital History Tel.: +352 46 66 44 9029 E-mail: marten.during@uni.lu

day, collections within the cultural heritage and digital humanities domains typically consist of digitized multimedia objects with a strong bias towards unstructured text, metadata in various levels of detail and completeness and often a layer of named entity annotations. Scholars in the humanities and related domains struggle to critically assess the value of and the biases inherent in such collections [1]. To this end they need to comprehend how it is organized and need to be able to search for and find relevant content in an exploratory manner without following predefined tasks [2,3]. This requires novel search and discovery tools which enhance well-established techniques such as faceted search and keyword search [4].

Interactive graph visualizations have been considered useful for these requirements [5–11]. Network data is often generated automatically by means of Named Entity Recognition (NER) such as e.g. persons, locations and organizations, paired with the manual or computational extraction of relations between them. While most applications today use unipartite or bipartite graphs, multilayer graphs allow for more complexity in the exploration of named entities, documents and the relations they share with each other [12]. In order to benefit from the analysis of interconnections within such corpora, humanists need to adapt and adjust their workflows. Most of the target users do not have a strong background in advanced data analysis but value very highly an at least basic comprehension of the inherent logic of the tools they work with [13, 14]. Moreover, imperfections within the data may cause significantly skewed results and therefore need to be taken into account. Such imperfections may stem from automated processing of digitized materials e.g. by OCR or NER but also from manual curation of e.g. metadata as well as intrinsic ambiguities of the source material. Since data cleaning is typically too costly, we observe a strong need for systems which let users cope with data-inherent imperfections. These requirements present interesting challenges and opportunities for the design of innovative tools for visual analytics.

This paper presents the concepts of the visual analytics platform Intergraph and reports the results of a first expert user testing. Intergraph is being developed as part of the BLIZAAR project, a French-Luxembourgish funded research project with the objective to develop visual analytics techniques for complex data modeled as dynamic multilayer graphs for domain experts in history and biology. Its principal use case consists of a collection of 15.000 digitized documents on European Integration since 1945. The next section reviews the state of the art in the visualization of dynamic multilayer networks. Section three presents the data structure followed by an overview of Intergraph's main features in section four. Section five gives an account of the conducted user tests. Finally, section six concludes the paper with a discussion and an outlook to future work.

2 State of the art

Network visualizations offer a unique way to understand and analyze complex data by enabling users to inspect and comprehend relations between individual units and their properties [15]. Some scientific fields have been using network visualizations for a long time, most notably systems biology where purpose-built visualizations are being developed for more than twenty-five years [16–18]. In Digital Humanities research we observe two types of network visualizations: (1) Manually compiled datasets based on network theory- and question-driven models of complex social relationships created to be analyzed by researchers [19], (2) Applications for the distant reading of graph visualizations of larger datasets which were created typically using methods borrowed from Natural Language Processing. Such applications encourage an audience with an interest in the respective topics to explore the data [9].

A preceding study by the BLIZAAR project on visual analytics requirements for research in digital cultural heritage has been published in [12]. The authors suggest that the data structures supporting the analysis of a complex digital corpus, in which people, organizations, places, multimedia documents and document collections are connected across time, should best be modeled as a dynamic multilayer network. Dynamic networks represent relationships between entities that evolve over time [20]. In multilayer networks, sub-networks are represented on independent layers, but they can also interact with each other [21]. Multilayer networks can have multiple types of node [22], with different attributes [23], and different types of relationships [24]. The particularities of dynamic multilayer networks and their importance for real-world applications have recently come to attention in network science. This led to increased work on their definition, analysis and visualization. In the last years, two European collaborative projects were entirely dedicated to this topic.

2.1 Plexmath

The Plexmath project (2012-2015) [25] aimed at formulating a new mathematical framework for the analysis of multi-level time-dependent complex networks. Several visualization methods have been published in the scope of this project. Pymnet [26] is a prototype to visualize graph data specifically described in compliance with Kivelä's general definition for multiplex and multilayer networks [21]. After loading the graph, the user can draw customized network images and save them in vector or raster formats. MuxViz [27] is an open-source platform for the exploration and interactive visualization of dynamic multilayer networks. In particular, the software provides a collection of algorithms for multilayer network analysis.

2.2 Multiplex

The objective of the Multiplex project (2012-2016)[28] was understanding the functioning of multi-level complex systems. Just as in Plexmath, a number of novel visualization methods have been conceived. Multinets.io [29] is a web-based visualization platform which has been designed and implemented at ETH Zurich for demonstrative purposes. The software illustrates a set of universal functionalities that are pertinent to the visualization of dynamic multi-layered graphs. Multinets [30] is a library consisting of reusable HTML components which provide functions to easily integrate the visualization of multilayer network data in a web page.

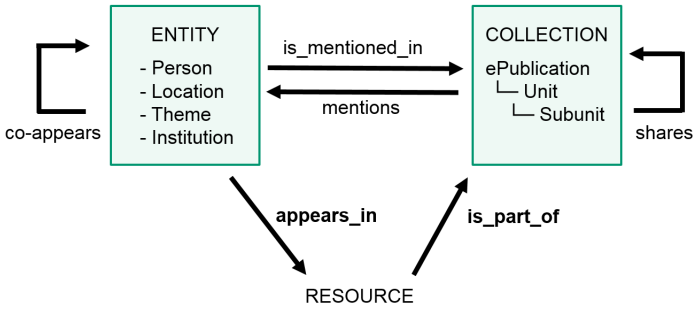
All of these applications, stand-alone or web-based, are primarily designed to either demonstrate concepts, or to render universal visualizations for (dynamic) multilayer graphs. However they are not directly applicable to visual analytics purposes in that they do not provide adequate functionality for domain-specific user tasks. After loading and visualizing a graph, interactivity is typically limited to node inspection, layout rearrangement and camera movement. In particular, the applications process complete networks without much possibility to query subnetworks or to create other visualizations for further exploration. While such kind of overall view might be adapted for relatively small sample data, it is not appropriate for larger real-world use cases.

3 Dataset and Requirements

The data is derived from resources on the European integration since 1945 collected by Centre Virtuel de la Connaissance sur l'Europe (CVCE) [31], a former research and documentation center which in 2016 was integrated into the University of Luxembourg. CVCE created a multilingual collection of ca. 25.000 digitized documents organized in 29 hierarchically organized thematic corpora. The documents differ significantly in nature: among them are newspaper articles, diplomatic notes, personal memoirs, audio interview transcripts, cartoons and photos with descriptive captions. The histograph project [6] processed a subset of circa 15.000 of these documents with named entity recognition (NER) and -disambiguation and stored co-occurrence links between entities and documents in a Neo4j graph database. This dataset was made available to and further processed by the BLIZAAR project for the development of more advanced graph exploration tools.

Figure 1 shows the used histograph data structure with their nodes and relationships. On the one hand, resources are part of one or more collections, from the highest logical unit of thematic corpora (ePublications) down to the corresponding hierarchical units and subunits, which is modeled by the "is_part_of" relationship. On the other hand, named entities (persons, locations, themes, institutions) have been extracted using Named-Entity Recogni-

Fig. 1: histograph/BLIZAAR data structure (nodes and relationships)



tion software such as YAGO [32] and TextRazor [33]. This process allowed generating the "appears_in" relationship. Entities "co-appear" in resources, and collections "share" resources, by bipartite network projection [34]. Finally, a collection "mentions" an entity, and accordingly the entity "is_mentioned_in" the collection, if the collection contains at least one resource where the entity appears. Table 1 gives an idea of the size of the dataset.

The data structure is a dynamic multilayer network:

- Nodes can be considered on two layers, an entity layer and a collection layer, and they have different relationships;
- Nodes of each layer have types: entities can be persons, locations, institutions or themes, collections can be epublications, units or subunits;
- Resources are time-stamped by their historic publication date. Therefore, the network changes depending on the considered time period.

In workshops and regular exchanges domain experts identified content retrieval and insights concerning the representation and interconnections of entities in a corpus as main objectives, by drafting the following user story:

"I would like to have an *overview* of how a specific person, institution or location is represented in the corpus, and of the other entities with whom they are mentioned. I would like to *compare* entities and explore where they share links. This helps me to decide which *documents* I want to study in greater detail".

Table 1: Histograph dataset magnitudes.

Item	**Approximate count**
Resources	15.000
Collections	4.000
Identified entities	36.000
Entity appearances	300.000
Entity co-occurrences	7.000.000

To achieve this within a graph-based environment users need to:

1. Create manageable subgraphs from the master graph
2. Compare multiple graphs
3. Observe temporal changes
4. Filter for node and resource properties
5. Maintain a straightforward link to the underlying resources
6. Handle inherent data imperfections

As a matter of fact, a specific problem due to the automatic generation of the network are data imperfections. Most commonly we observe fragments which were wrongly identified as entities, duplicate entities which have not been disambiguated correctly, and entities which have been disambiguated wrongly and linked to homonyms ("Robert Schuman"). An effort to rectify all of the abovementioned flaws is too costly and therefore unrealistic for this and comparable corpora. Functionalities moderating those flaws were therefore considered to be the most promising strategy in this case.

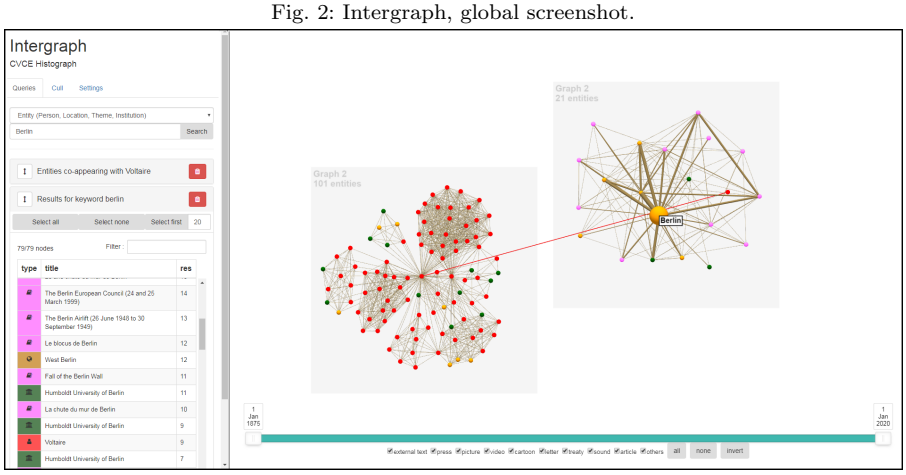
4 Intergraph

The visual analytics tool Intergraph offers a novel approach to exploring Digital Humanities corpora by means of an iterative search and discovery workflow. Written in javascript, Intergraph runs in a web browser and communicates with a node.js server which queries the data from a Neo4j database. The front-end client renders the graphs using the Three.js graphics library.

Given the size of the histograph dataset, an overall visualization of the corpus is neither suitable nor desirable for exploration. Users are rather interested in creating and inspecting subnetworks with entities relevant to their current research interest. Therefore, the main idea of Intergraph is to begin the exploration from one or more known start nodes. Following the expand-on-demand principle [2], the user will encounter new relevant nodes and pursue their exploration by conveniently creating additional graphs stemming from the existing ones. This path of exploration yields a sequence of linked subgraphs (user requirement 1).

Figure 2 shows a global screenshot of the Intergraph interface. Graphs can be dynamically added to and deleted from the scene. Following the VisLink approach [35], they are rendered on free-floating planes which can be arbitrarily translated, oriented and scaled using familiar transformation widgets. Depending on the user tasks and preferences, the scene can be viewed in a 2D or a 3D perspective. The default 2D view is known to be most efficient for visual data exploration and analytics, since 3D visualizations tend to suffer from occlusion, overlapping and distortion, and they often require increased viewpoint navigation to find an optimal perspective [36]. 3D scenes allow however

Fig. 2: Intergraph, global screenshot.



to stack planar graph layers in space and to create so-called 2.5D visualizations, which can have their virtue for understanding complex networks [37].

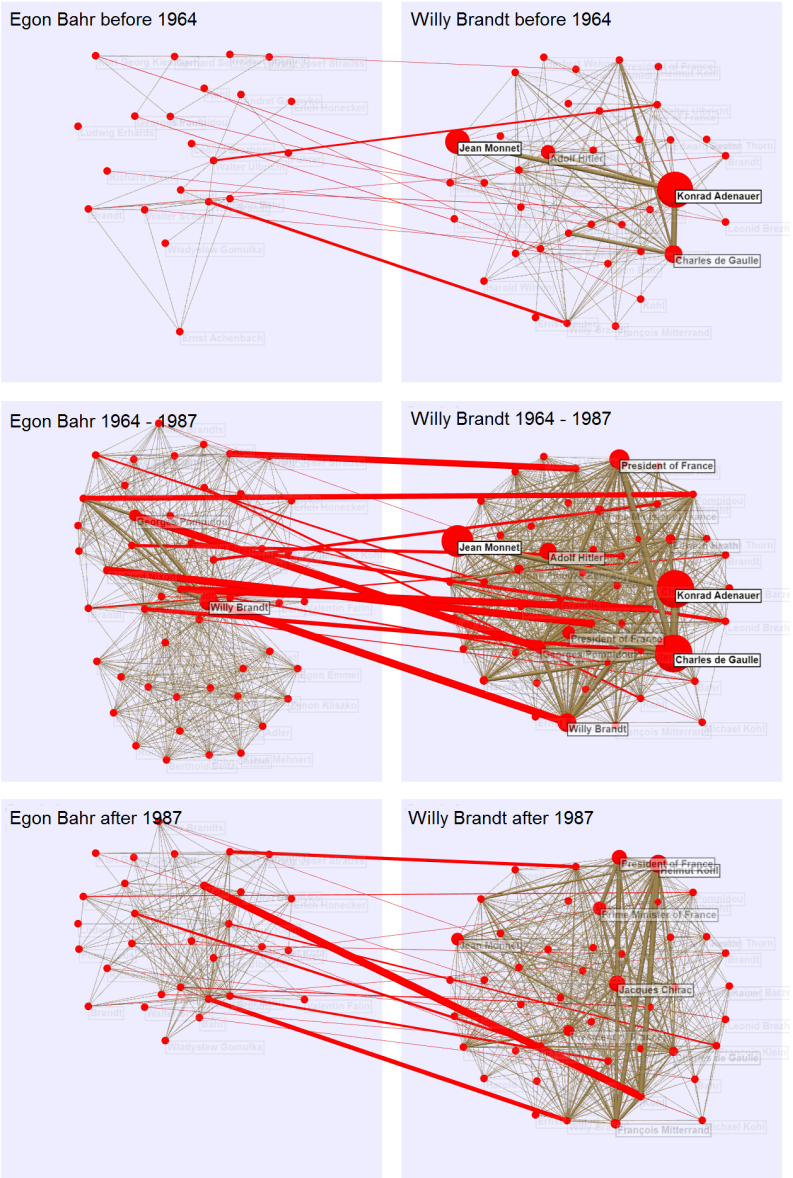
Since target users are not necessarily experts in network science, Intergraph forgoes advanced graph concepts and metrics like clustering coefficients or betweenness. Node colors reflect the node type, and sizes indicate the number of underlying resources. A click on a node or edge gives immediate access to these resources (user requirement 5). New graphs are typically produced by querying 1.5D ego-networks of existing nodes, via easy-to-communicate operations such as

- All entities co-appearing with a given entity
- All collections mentioning a given entity
- All entities mentioned in a given collection
- All collections sharing resources with a given collection

If the same node appears on two or more graphs of the scene, interedges are drawn (see Figures 2 and 3). This approach of user-driven network generation was partly inspired by "citation-chaining", one of the most commonly used search strategies for literature among historians [38,39]. Intergraph applies the citation chaining principle to documents and the entities mentioned in them. This allows users to create their own interest-driven search and discovery paths across the dataset.

With regard to the imperfect data, the most frequent flaw encountered with entity disambiguation are multiple recognized entities where in reality only one was mentioned. For example, the Named-Entity Recognition yielded three separate nodes for "East Berlin". If the user wants to consider these three nodes as one in order to create an ego-network, it is possible to multi-select a number of nodes, and to query "All entities co-appearing with a given

Fig. 3: Co-evolution of two dynamic networks over consecutive time periods.



entity (union)" meaning that the result will be the list of nodes co-appearing with at least one of the selected nodes. The user can then define a unique groupnode for "East Berlin" and draw a meaningful graph (user requirement 6). It is also possible to query "All entities co-appearing with a given entity (intersection)". This operation returns the list of entities co-appearing in the

corpus with all selected nodes and can be used to merge multiple nodes e.g. if understood as representatives of a social group.

Results to new queries first appear in the form of a table in the left pane. This first kind of visualization, itemizing only the nodes without the edges, may in some cases already be sufficient to work with. The table lets users decide whether it is worth generating the graph or to recompile the list of nodes, in case of missing nodes or nodes which should be excluded from the graph. A graph of a given node table, or a part of it, can be generated on demand, and it is added to the canvas on the right side of the interface.

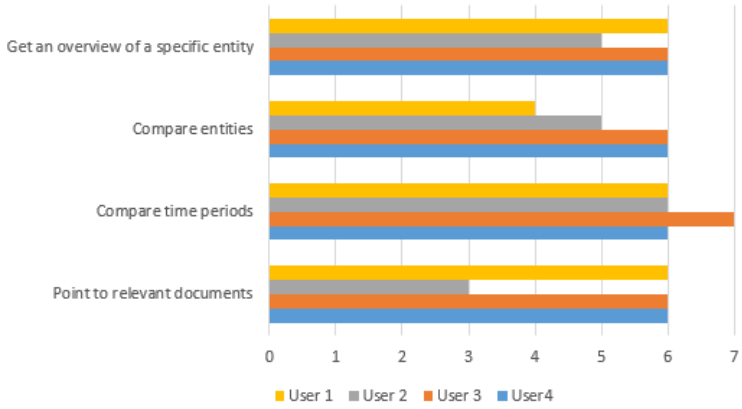
The scene can be submitted to a filter which operates on resource type and time (user requirement 4). Subgraphs of a given resource type can provide a better understanding of its distribution within the corpus. Subgraphs considering the resources of a specific time window allow assessing the relevance and interconnections of entities during a considered period. The user can shift the time window and get an animated representation of the dynamic graph (user requirement 3). If time-to-time mapping, i.e. animation, is not convenient to analyze the evolution of a network over time, time-to-space mapping is also possible. For this purpose the user can clone and "freeze" a graph of the scene, meaning that its current filter is fixed. By this means, several graphs with the same nodes but distinct time periods can be juxtaposed (2D) or superimposed (3D) in space [20]. As an example, Figure 3 illustrates the dynamics of two related ego networks: Willy Brandt, former chancellor of the Federal Republic of Germany, and his advisor Egon Bahr. The graphs are filtered and frozen for three consecutive time periods (before 1964, 1964-1987, after 1987) and reveal how the co-occurrence networks evolve and overlap (user requirement 2).

5 User test results

A formal user evaluation was held at the Luxembourg Center for Contemporary and Digital History (C2DH), in order to assess how well the previously identified user story has been implemented in Intergraph. The tests were conducted with a group of four scholars, all of whom were former employees of CVCE. The selection criteria were familiarity with the underlying corpus on European integration, as well as with the application of digital tools and methods. Both criteria were put in place to ensure that, for one, users could turn their attention to the interaction with the prototype with only minimal reminders of the underlying data model and content, and for another, they were qualified to judge the pertinence of Intergraph's output.

After a brief introduction to the functionalities of the platform, users were invited to use Intergraph for themselves and to begin their session with an elementary keyword search for an entity they knew was mentioned in the corpus. From this starting point, they were free to perform more synoptic tasks, such

Fig. 4: User test questionnaire results.



as finding relevant collections and resources, searches for co-appearing entities and comparison of their corresponding networks, in order to get a comprehensive view of how the investigated element is represented, positioned and linked in the corpus. Throughout the session, users were encouraged to continuously verbalize their train of thoughts and actions following the thinking aloud approach [40].

Following the 45 minute testing period users were asked to give verbal feedback and to complete a questionnaire. Concerning verbal feedback, users appreciated the ease of navigating through the corpus, the flexibility and freedom to combine different elements, the links across canvases, the management of duplicate entities as well as the ability to drill down to the underlying resources. In the questionnaire, users were invited to rate on a scale of 1 to 7 the utility of Intergraph with view to all aspects of the initially defined user story. As a result, Figure 4 shows a high general acceptance. In particular, all users declared that for the given user story they would prefer to use Intergaph over the other available tools (CVCE homepage search and CVCE backend search).

6 Conclusion & future work

This paper presented Intergraph, a visual analytics platform dedicated to the effective navigation through the content of Digital Humanities corpora. The work is inspired by recent advances in the visualization of dynamic multilayer networks, and has been enhanced and optimized for humanists and their domain-specific workflows. The conducted user tests showed a high acceptance of the tool with respect to the original requirements.

Given the exploratory nature of Intergraph, future work will concentrate on additional ways to suggest related nodes, and to create pertinent graphs out of existing ones, for example by applying recommendation algorithms [41]. The multilayer character of the data should be leveraged by adding other types of interlayer edges, such as those indicating the "mentions" relationship between collections and entities. Finally, it is important to observe that the used data structure is highly generic. As a matter of fact, entities identified in collections of timestamped resources are likely to be found in a huge number of digital corpora. Therefore, it is planned to open the existing platform to other data sets, so that it can evolve into a valuable visualization and exploration tool for many scholars working in the field of Digital Humanities.

7 Acknowledgments

This work was funded by the ANR grant BLIZAAR ANR-15-CE23-0002-01 and the FNR grant BLIZAAR INTER/ANR/14/9909176.

References

1. Lara Putnam. 2016. The Transnational and the Text-Searchable: Digitized Sources and the Shadows They Cast. The American Historical Review 121, 2: 377–402.
2. F. van Ham and A. Perer. 2009. Search, Show Context, Expand on Demand: Supporting Large Graph Exploration with Degree-of-Interest. IEEE Transactions on Visualization and Computer Graphics 15, 6: 953–960.
3. Stephen C. Brown and Mark Greengrass. 2006. RePAH: a user requirements analysis for research portals in the arts and humanities. Humanities Research Institute Online, Sheffield University.
4. Florian Windhager, Paolo Federico, Günther Schreder, Katrin Glinka, Marian Dörk, Silvia Miksch, Eva Mayr, Visualization of Cultural Heritage Collection Data: State of the Art and Future Challenges, IEEE Transactions on Visualization and Computer Graphics, vol. 25, pp. 20, 2018.
5. S Jänicke, G Franzini, M F Cheema, and G Scheuermann. On Close and Distant Reading in Digital Humanities: A Survey and Future Challenges. 21.
6. Daniele Guido, Lars Wieneke, and Marten Düring. 2016. histograph. Graph-based exploration, crowdsourced indexation. CVCE, Luxembourg.
7. G. Moretti, R. Sprugnoli, S. Menini, and S. Tonelli. 2016. Knowledge-Based Systems ALCIDE : Extracting and visualising content from large document collections to support humanities studies. Knowledge-Based Systems 111: 100–112.
8. Christopher Warren, Daniel Shore, Jessica Otis, Lawrence Wang, Mike Finegold, and Cosma Shalizi. 2016. Six Degrees of Francis Bacon. A Statistical Method for Reconstructing Large Historical Social Networks. Digital Humanities Quarterly 10, 3.
9. Marten Düring. 2019. Gleanings from applications for the graph-based exploration of cultural heritage collections. In F. Kerschbaumer, L. von Keyserlingk, M. Stark, and M. Düring, eds., The Power of Networks. Prospects of Historical Network Research. Routledge Publishers.
10. Martyn Jessop. 2008. Digital visualization as a scholarly activity. Literary and Linguistic Computing 23, 3: 281–293.
11. Nadia Boukhelifa, Emmanouil Giannisakis, Evanthia Dimara, Wesley Willett, and Jean-Daniel Fekete. 2015. Supporting Historical Research Through User-Centered Visual Analytics. In: Bertini, E., Roberts, J.C. (eds.) EuroVis Workshop on Visual Analytics (EuroVA), pp. 1–5 (2015).

12. McGee, F., Düring, M. and Ghoniem, M., 2016. Towards Visual Analytics of Multilayer Graphs for Digital Cultural Heritage. 2016 Workshop on Visualization for the Digital Humanities (Extended Abstracts), an IEEE Vis workshop.
13. Benjamin Bach, Nathalie Henry Riche, Roland Fernandez, Emmanoulis Giannisakis, Bongshin Lee, and Jean-Daniel Fekete. NetworkCube: Bringing Dynamic Network Visualizations to Domain Scientists. Posters Compendium of InfoVis 2015.
14. A. Katifori, E. Torou, C. Vassilakis, and C. Halatsis. 2008. Supporting Research in Historical Archives: Historical Information Visualization and Modeling Requirements. 2008 12th International Conference Information Visualisation, 32–37.
15. Rossi, L., Magnani, M.: Towards effective visual analytics on multiplex and multilayer networks. Chaos, Solitons & Fractals 72(0), 68–76 (2015) .
16. P. Mendes, GEPASI: a software package for modelling the dynamics, steady states and control of biochemical and other systems, Computer Applications in the Biosciences 9 (5): 563-571, 1993.
17. Shannon P, Markiel A, Ozier O, Baliga NS, Wang JT, Ramage D, Amin N, Schwikowski B, Ideker T. Cytoscape: a software environment for integrated models of biomolecular interaction networks. Genome Research 2003 Nov; 13(11):2498-2504.
18. Georgios A. Pavlopoulos, Sean I. O'Donoghue, Venkata P. Satagopam, Theodoros Soldatos, Evangelos Pafilis, and Reinhard Schneider. Arena3D: visualization of biological networks in 3D. BMC Systems Biology 2008, 2:104.
19. Marten Düring. 2013. HNR Bibliography. Historical Network Research. Retrieved September 1, 2018 from http://historicalnetworkresearch.org/bibliography/
20. Beck F., Burch M., Diehl S., Weiskopf D.: The state of the art in visualizing dynamic graphs. In EuroVis - STARs (2014), EuroVis '14, Eurographics Association, pp. 83–103.
21. M Kivelä, A Arenas, M Barthelemy, JP Gleeson, Y Moreno, MA Porter (2014), Multilayer networks, Journal of Complex Networks 2 (3), 203-271.
22. S. Ghani, B. C. Kwon, S. Lee, J. S. Yi, and N. Elmqvist. Visual analytics for multimodal social network analysis: A design study with social scientists. IEEE Transactions on Visualization and Computer Graphics, 19(12):2032–2041, 2013.
23. A. Kerren, H. C. Purchase, and M. O. Ward. Multivariate network visualization. Lecture Notes in Computer Science, 8380, 2014.
24. L. Singh, M. Beard, L. Getoor, and M. Blake. Visual mining of multimodal social networks at different abstraction levels. In Information Visualization, 2007. IV '07. 11th International Conference, pp. 672–679, July 2007.
25. https://cordis.europa.eu/project/rcn/105293_fr.html
26. http://www.mkivela.com/pymnet/
27. De Domenico, M., Porter, M.A., Arenas, A.: MuxViz: a tool for multilayer analysis and visualization of networks. Journal of Complex Networks (2014).
28. https://cordis.europa.eu/project/rcn/106336_en.html
29. https://multinets.io/
30. Piškorec, Sluban, Šmuc (2015), MultiNets: Web-Based Multilayer Network Visualization, in Machine Learning and Knowledge Discovery in Databases, pp.298-302.
31. https://www.cvce.eu/
32. Max-planck-institut fur informatik: YAGO. https://www.mpiinf.mpg.de/departments/databases-and-informationsystems/research/yago-naga/yago/
33. The natural language processing API. https://www.textrazor.com/
34. K. A. Zweig and M. Kaufmann, "A systematic approach to the one-mode projection of bipartite graphs," Social Network Analysis and Mining, vol. 1, no. 3, pp. 187–218, 2011.
35. C. Collins and S. Carpendale, "VisLink: Revealing Relationships Amongst Visualizations," IEEE Trans. on Visualization and Computer Graphics (Proc. of the IEEE Conf. on Information Visualization (InfoVis)), vol. 13, iss. 6, 2007.
36. Shneiderman, B., Why not make interfaces better than 3D reality?, IEEE Computer Graphics and Applications., Nov.-Dec. 2003, Vol 23(6), pp. 12-15.
37. C. Ware, Designing with a 2 1/2D Attitude, Information Design Journal, Vol. 10, No. 3, pp. 171-182, 2001.
38. David Ellis. 1989. A behavioural approach to information retrieval system design. Journal of Documentation 45, 3: 171–212.

39. George Buchanan, Sally Jo Cunningham, Ann Blandford, Jon Rimmer, and Claire Warwick. 2005. Information Seeking by Humanities Scholars. Research and Advanced Technology for Digital Libraries, Springer Berlin Heidelberg, 218–229.
40. T. Boren and J. Ramey. 2000. Thinking aloud: reconciling theory and practice. IEEE Transactions on Professional Communication 43, 3: 261–278.
41. Bobadilla, J., Ortega, F., Hernando, A., Gutirrez, A. Recommender systems survey. Knowl. Based Syst. 2013,46, 109–132.