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Visualizing Spatial Dynamic Networks with Force-Directed Graph Layout

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Abstract:

In this study, we investigate a thematic map for spatial dynamic networks using trading networks as example. This data is highly influenced by its time dependency. Visualizing this spatio-temporal data is crucial for making it accessible and interpretable to users. To ensure accurate interpretation, the data's temporal, spatial, and content-related components must be effectively represented. We present a visualization method that aims to preserve the spatial aspect of the data, defined by the geographic outline of the countries. This spatial context is vital to the network visualization, as the geographic proximity of trading partners heavily influences trade and it allows the user to identify the countries.

Existing research on network visualization can be categorized into several branches. Abstract static networks, i.e., networks without spatial or temporal information have been extensively studied, particularly in the fields of graph drawing, computer science, and information visualization. Node-link diagrams are a common visualization technique for such networks, where the network entities (*nodes*) are represented as disc-shaped symbols and the network connections(*edges*) as lines (Beck et al., 2017). Abstract dynamic networks are non-spatial networks where the entities and connections or their attributes change over time. For example, Beck et al. (2017) provide a taxonomy for visualizing dynamic graphs, while Barros et al. (2021) offer a comprehensive survey of embedding techniques for dynamic graphs. These works focus on abstract dynamic networks, highlighting temporal evolution without considering spatial attributes. Spatial static networks have been explored in cartography and related fields. Mashima et al. (2011) investigate methods for visualizing spatial networks, where geographic context plays a crucial role, but their work does not address temporal dynamics. Combining spatial and temporal aspects, spatial dynamic networks have received limited attention. For other types of spatial dynamic data, several approaches introduce interactive visualization concepts and algorithms. For example, Nickel et al. (2022) propose a method for generating dynamic Demers cartograms using linear programming, focusing on rectangular objects. However, their approach does not support network data with nodes and edges and, also, it does not support disc-based representations. Our study bridges these gaps by proposing a visualization method tailored for spatial dynamic networks, drawing on concepts from graph drawing, information visualization, and cartography.

In this study, we combine node-link diagrams (Beck et al., 2017) with proportional symbol maps where nodes are represented by discs, with the size of each disc encoding the trading volume of the corresponding country. To enhance the interpretability of the visualization, each disc can display the country's flag or provide additional information when hovered over. The trading volume between two countries is represented by the weight of the connecting edge, visually indicated by the thickness of the corresponding line. A connecting edge is only displayed if there is trade between the two countries during the selected time epoch. Both a country's overall trade volume and its trade relationships with individual partners vary over time. Our visualization allows an interactive exploration of the changes over time through an interactive time slider. It enables users to explore the temporal evolution of the network by setting a specific year to be visualized.

A simple approach for generating a node-link diagram of spatial data is to place each disc's center at the geographic location of its corresponding country, e.g., the country's centroid, as shown in Figure 1a. We call such a visualization *spatially accurate*. A typical requirement for node-link diagrams is to avoid overlapping discs which can be achieved by scaling down all discs. Often, this results in a visualization of poor quality because many discs become too small to be visible, especially when viewing the entire network. Additionally, the visualization tends to lack compactness due to high node density in regions such as Europe, contrasted with low density in areas like the oceans.

In this study, we relax the constraint of strict spatial accuracy to solve the described problems of *spatially accurate* visualizations. Specifically, we allow discs to be positioned away from their exact geographic locations while preserving the relative spatial relationships that are essential for understanding the geographic context. Additionally, we permit discs to be placed at different positions for every time epoch. This flexibility enables a more compact visualization with larger discs, improving readability and interpretability. The outcomes of this approach are illustrated in Figure 1b. However,

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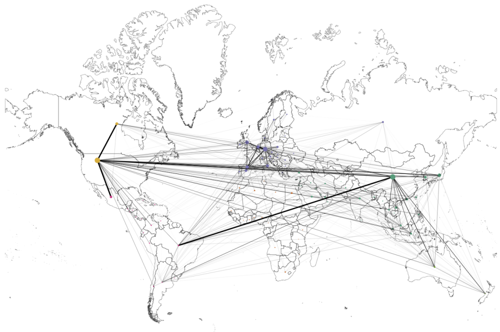
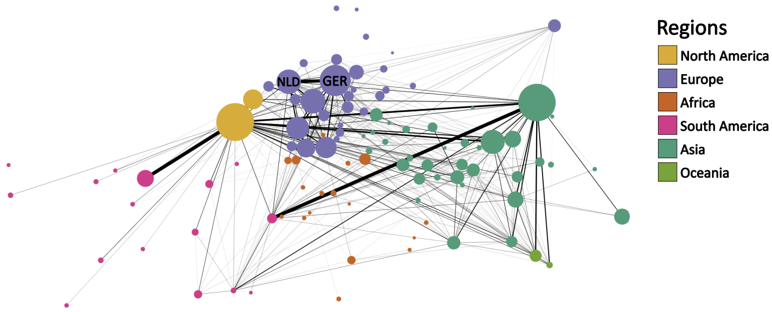


(a) non-displaced, spatially accurate



(b) our displaced visualization

Figure 1. Global trading network in 2019. (b) We highlight the nodes of the Netherlands (NL) and Germany (GER). Data obtained from World Trade Organization (2024)

this added flexibility also introduces the risk of losing spatial context and may lead to undesirable behavior in time-slider interactions due to excessive movement of discs between consecutive time epochs. These drawbacks are mitigated by our optimization approach. We focus on four aspects for the optimization of the node centers of all discs for every time epoch.

1. **Node proximity:** Connected nodes should be placed close together, with the weight of their connecting edges defining how attracted two nodes are to each other. For our example of trading networks this highlights the economic proximity between countries. Nodes without a connection should be placed further apart.
2. **Spatial relationships:** While relaxing strict spatial accuracy, the spatial orientation of neighboring countries should be preserved. We define spatial orientation as the angle at one country's geographic position between the north direction and the other country's exact geographic position. This is achieved by using their exact geographic positions as the starting point for optimization. The spatial orientation is maintained by adjusting the positions of discs representing countries that share a common border, ensuring that their spatial orientation is stabilized concerning their initial spatial orientation.
3. **Temporal consistency:** To ensure smooth time-slider interactions, we stabilize the node positions over time.
4. **Disc size:** We aim for a compact layout so that the overall layout is small and, hence, the relative disc sizes are large.

We suggest a heuristic optimization of the problem with a force-directed algorithm, which optimizes the layout by balancing all four aspects. The objectives are introduced into the optimization by formulating a corresponding force, which is calculated based on the spatial positions of the countries and the dynamic network. Figure 1b shows the visualization that was generated using our described method. Preliminary experiments show that our approach enables the radii of the nodes to be more than 5 times larger for the displaced visualization in Figure 1b compared to the spatially accurate variant in Figure 1a, improving both the readability and interpretability of the network.

For future work, we plan to evaluate our force-directed algorithm. We will explore quality metrics for evaluating the results, allowing a comparison between different variants of our force-directed algorithm with different weightings of the forces. We provide an interactive demo under `https://www2.geoinfo.uni-bonn.de/html/visualization/tradenetwork/`. In the evaluation, we compare our spatially displaced version with an abstract variant and a spatially accurate variant, highlighting the trade-offs between spatial accuracy, visual clarity, and network representation. In addition to exploring quality metrics, we plan to conduct a user study to assess the effectiveness of the different approaches, providing valuable insights into the user experience and overall performance of each method.

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