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Exploring the Design Space of Sankey Diagrams for the Food-Energy-Water Nexus

Brandon Mathis

Yuxin Ma

Michelle Mancenido

Ross Maciejewski
Arizona State University

In this work, we define a set of design requirements relating to Sankey diagrams for supporting Food-Energy-Water (FEW) nexus understanding, and propose the NEST diagram design, a visualization design that incorporates a number of characteristics from Sankey diagrams, treemaps, and graphs, to improve readability and minimize the negative impact of edge crossings common in traditional Sankey diagrams.

In recent years, there has been an increasing focus on the dynamics, interactions, and feedbacks between the food, energy, and water sectors, or the so-called food-energy-water (FEW) nexus. By better understanding the interdependencies between these sectors, policy makers hope to increase energy efficiency, reduce water usage, alter crop portfolios, and help shape future policy decisions. What previous work has shown is that researchers and stakeholders primarily choose to visualize the FEW nexus as one unified system, most commonly with a Sankey Diagram. This unified view enables them to explore linkages across sectors and hypothesize about how changes in one sector may affect another. However, as more sectors, resources and demands are explored, the Sankey Diagram representation faces significant design challenges.

In this paper, we explore the design space of the Sankey diagram, with a focus on how to improve this diagram to better support the exploration and analysis of a FEW nexus. We define a general task taxonomy and propose a set of design alternatives to support various FEW nexus visualization tasks. We compare the proposed design alternatives against the traditional Sankey diagram through a user study, and lessons learned and future directions are discussed. By focusing on a visualization type (Sankey Diagram) that is used across disciplines, we hope to effectively promote interdisciplinary collaboration and explore how visualization development in this space could help provide a better understanding of FEW nexus interactions, support FEW policy-making under uncertainty, and facilitate identification of critical design requirements for FEW visualizations.

RELATED WORKS

Sankey Diagram are highly related to graph visualizations, and significant amounts of work have focused on improving graph designs[9]. This includes the works by Breitkreutz et al.,[5] which looks to improve network aesthetics using user-implemented node relaxation, and Alemasoom et al.,[2] which looks to reduce edge crossings in Sankey diagrams, primarily through the use of artificial nodes. Large scale FEW analysis can be seen in Soundararajan et al., [10] who develop a framework for Sankey diagram use when presenting energy and exergy flows at national and facility level scales, Greenberg et al.,[6] who develop hybrid Sankey diagrams fors multisector (energy and water) usage at a state level, Bijl et al., [4] who examine the FEW nexus at different spatial scales, and Yang et al.[12], who examine the food, energy, and water nexus at a regional scale in the Great Ruaha River of Tanzania.

Currently, there are two main issues with visualization research for the FEW nexus. First, there is no existing work on exploring the design space of Sankey diagrams in the application of FEW nexus. Second, existing design studies on general graphs and Sankey diagrams mainly focus on better positioning nodes, grouping edges to reduce the impact of edge crossings, scaling, and manual diagram layouts, rather than exploring other design elements that could make the diagram easier to comprehend without relying primarily on the edges to disseminate information. Our work fills this gap by exploring the design space and design decisions in addressing the tasks in the FEW nexus.

TASK TAXONOMY

Sankey diagrams appear in several disciplines and can be beneficial for explaining complex systems to non-experts that may play an important role in the operation of the system. However, little work has been done in the specification of task requirements to analyze the effectiveness of these diagrams. This poses a problem when attempting to develop new designs as there is no general metric for evaluating the improvement of the new design compared with the original Sankey diagram design. As such, we focus on first identifying common tasks that could apply to Sankey diagrams, then identify specific tasks relating to Sankey diagrams specifically in the FEW nexus. We accomplish this through a review of related work and discussions with domain experts. We worked with four domain experts from sustainability science and international development, hydrology and atmospheric sciences, system modeling, and decision science. These domain experts provided a diverse range of expertise that encapsulates the majority of the disciplines present in the FEW nexus. In the early stages of the diagram design process, these domain experts identified tasks they would like to be able to perform, and questions they would like to be able to answer using a diagram of the FEW nexus. First, we asked the domain experts to identify high-level tasks that they may perform. After these high-level tasks were identified, we presented a list of low-level tasks to the domain experts that we felt were representative of the given high-level tasks. Further feedback from the domain experts helped us refine whether these low-level tasks were an accurate representation of their original high-level tasks. This process was then iterated until the domain experts felt that our low-level tasks fit the original high-level tasks.

From our review of the Sankey diagram literature and domain expert discussions, we identified seven major task categories for Sankey Diagrams. Although these task categories were developed specifically with Sankey diagrams in mind, many of these are also applicable to a number of other flow diagram designs and application areas outside of the FEW nexus. The set of task categories include:

Object Identification (OI), derived from Laha et al.,[8] refers to identifying specific nodes or specific supernodes based on a set of given characteristics. These tasks include identifying the existence/absence of a node, identifying the name/type of a node, identifying sectors used in a node, and counting the number of supernodes with a given feature.

Value Retrieval (VR), derived from Amar et al.,[3] refers to identifying values relating to specific nodes, specific supernodes, or specific edges based on a set of given characteristics. These tasks focus on retrieving the value associated with inflows/outflows of resources, the amount of resource contributed from a specific parent node or supernode, and the amount of resource produced by a source node.

Link Analysis (LA), derived from Lee et al.,[9] refers to identifying high-level interactions between adjacent nodes or adjacent supernodes of similar and dissimilar types. These tasks include identifying parents of a single node or supernode, identifying children of a single node or supernode, identifying splits/merges of different resource types, and identifying conversions from one resource into another resource.

Path Analysis (PA), derived from Lee et al.,[9] refers to identifying high-level interactions between nodes and edges from an initial source to the final destination. These tasks include identifying the existence/absence of a path, finding a path of a specific resource from the source to a potential final destination, and finding all paths of a specific resource from the final destination to the potential sources.

Pattern Recognition and Column Understanding (PRCU), derived from Amar et al.,[3] Ahn et al.,[1] and Laha et al.,[8] refers to the identification of trends or repeated characteristics occurring within single or multiple diagrams. These tasks include intra-column understanding and patterns.

Extremum Identification (EI), derived from Amar et al.,[3] refers to identifying the extreme values either locally or globally within the visualization. These tasks include identifying the maximum/minimum local resource type supply/usage and identifying the maximum/minimum global resource type supply/usage.

Inter-sector Analysis (IA) refers to the analysis of inter-sector influence and interaction within a single or multiple diagrams. These tasks include inter-sector influence and inter-sector resource usage.

These task categories are used as the basis for the diagram design requirements as well as the user study questions designed to compare the within task effectiveness across different Sankey-like visual representations.

NEST: NETWORK EMBODIED SECTORAL TRAJECTORY DIAGRAM

Based on discussion with our domain experts, the task categories of value retrieval, link analysis, and inter-sector analysis were identified as their major challenges in using the Sankey diagram. This helped to isolate which elements of the Sankey diagram had the most potential to benefit from a new visual design. Through an iterative design procedure with our FEW nexus stakeholders, we developed the NEST diagram designs that incorporate characteristics from Sankey diagrams, treemaps, and graphs, to improve readability for multi-sector designs, such as those found in the FEW system.

The majority of elements and design choices used in the NEST designs stem from Sankey diagrams. These include resource flow from left to right, column-based semantic node placement, size of elements representing the amount of a resource, and abstraction of resource flows after they pass through a node. These elements provide a generalized overview of the underlying system, introduce space and time into the design, and are generally non-expert friendly elements. The design elements used from treemaps were the partitioning of an element based on the amount of usage by the sub-elements. Although this is generally the same idea as Sankey diagram nodes being stacked together without spacing, the idea of clustering resources close together in our design drew a significant amount of inspiration from treemaps. The design elements drawn from graphs were uniform sized edges and uniform sized nodes. A large amount of work has also been done in graph layout optimization and graph aesthetics including the works by Selassie et al.[11], Alemasoom et al.[2], Bennett et al[7], and Breitkreutz et al.[5], and having the ability to use these techniques for minimizing edge crossings is very important, and will continue to be important, in further optimization of flow diagram designs.

The general design for the NEST diagram also largely benefited from the idea of artificial nodes proposed by Alemasoom et al.[2] In their work, artificial nodes were used to minimize edge intersections within a Sankey diagram. This idea was used in the NEST diagram to route edges from intermediate columns of the diagram to the last column of the diagram without conflicting with the proceeding columns. A sample of one of the NEST diagram designs with the corresponding original Sankey diagram can be seen in Figure 1.

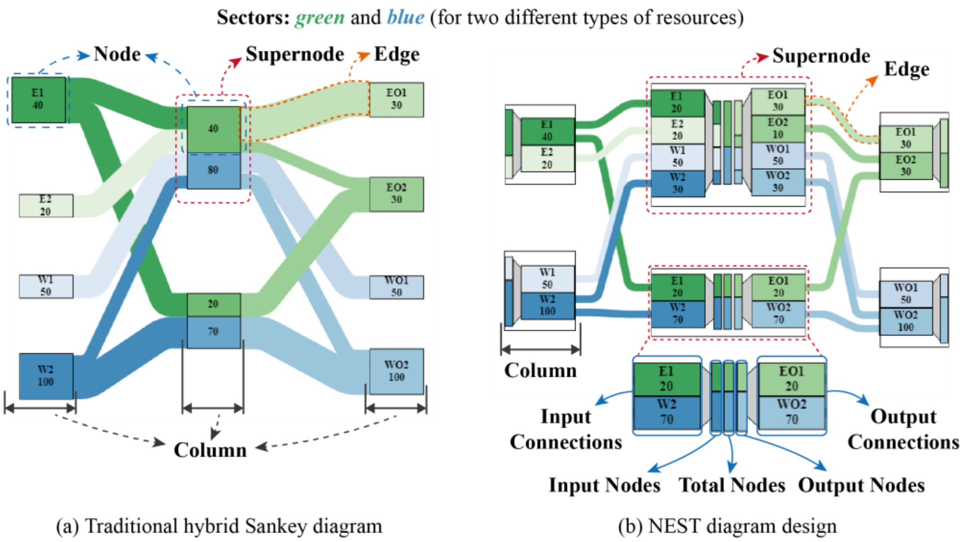

Figure 1. Example of a) Traditional hybrid Sankey diagram, and b) the corresponding NEST diagram design representation of a sample data set.

Design Elements

For the NEST designs we identified 5 major design elements: nodes, sectors, supernodes, edges, and columns (Figure 1(b)). Although different definitions were needed for the specification of these elements, many of them share similar meanings or characteristics to their corresponding design element in Sankey diagrams. These design elements are based on elements identified within the Water-Energy Sankey diagrams produced by Greenberg et al.,[6] some of which do not explicitly appear in traditional Sankey diagrams. Figure 1 (a) shows an example of the Water-Energy Sankey diagram which contains the following elements:.

Node refers to an element that presents the amount of a resource either numerically or as a quantitative estimation based on height. In these designs we rely on the use of 5 different categories of nodes, these nodes represent the majority of the data in our diagram. These categories, seen in the supernode highlighted in Figure 1 (b), from left to right are input connection, input, total, output, and output connection. Input connection and output connection are the nodes that edges are connected to and provide a numeric value for the node as well as the name of the node that a node is connected to. Input, output, and total nodes are used to present a quantitative estimation of the nodes and can be compared to other similar nodes in the diagram by examining their height, which presents the amount of usage. These nodes draw inspiration from treemaps, in that, the total amount of resources used in a supernode is subdivided into the resources that contribute to or are produced in that supernode. This approach is also similar to how edges function in traditional Sankey diagrams, without requiring large edges to span large areas of the diagram. Looking at the zoomed-in supernode in Figure 1 (b), the leftmost two nodes are input connections nodes showing that 20 units of the energy resource E1 and 70 units of the water resource W2 are coming into this supernode. The two nodes to the right of these represent these values by the height of the nodes, the energy node is 1/2 the height of the node E1 in the first column with 20 units contributing to it. The nodes to the right of these nodes are total nodes and provide the sum of the resource sectors. As there is only one energy node and one water node, the height of these nodes is the same as the input nodes. The nodes to the right of these are output nodes, which function similarly to input nodes. These present how much of each of the total nodes is going to where next by the height of the node. Finally, the last nodes are output connection nodes and provide a numeric representation of the output nodes, showing that 20 units of the energy resource output EO1 is going to the energy resource in the final column and 70 units of the water resource output WO2 are going to the water resource in the final column.

Sector refers to a set of elements that contain a shared unit of measure, or other defining characteristic. Elements of different sectors do not explicitly interact with each other. In Figure 1, different Sectors (water, energy) are represented by different colors (blue, green).

Supernode refers to a collection of nodes from a single, or multiple, sectors that share a semantic meaning and are placed in close proximity. This is similar to a supernode in graph theory, as a large number of incident edges are present.

Edge refers to a connection between two nodes. The major difference being that in the Sankey diagrams, the thickness of the edge also represents the value of a resource that is flowing through it, whereas in our designs we maintain uniform edges, much like a graph.

Column refers to a set of supernodes that share a horizontal position and exhibit a similar semantic meaning. This is also seen in Sankey diagrams in terms of node position.

NEST Designs

Three different Nest diagram designs were developed. While overall the designs are very similar, small characteristic changes were introduced in an attempt to mitigate different issues that may be experienced from the different design choices. A sample representation of a hybrid energy-water system using the three different designs is show in Figure 2.

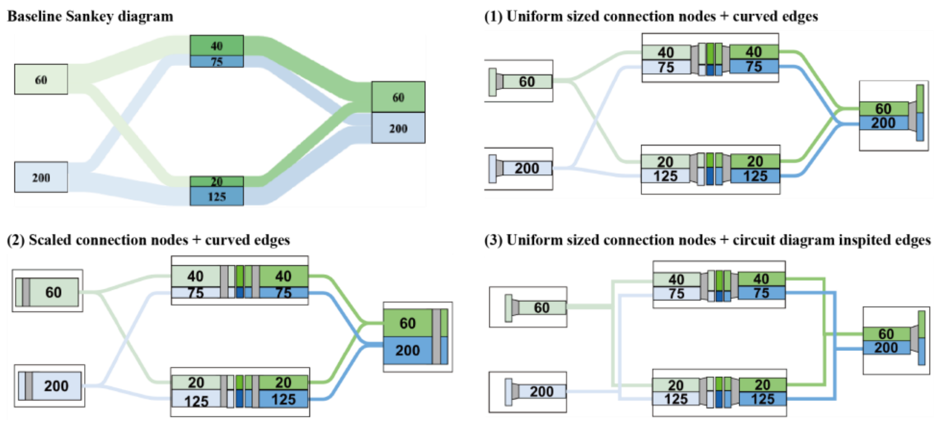

Figure 2. Samples of the three NEST diagram designs.

The first design (Figure 2 (1)) used uniform sized connection nodes with curved edge. Uniform sizes were used to only help present the connection between two nodes, while also minimizing the impact of the new nodes on the ability to quantitatively estimate values in the diagram. The drawback of the uniform approach is that all connection nodes are represented as the same size which could cause confusion since the input, output, and total nodes are given sizes based on their value.

The second design proposed (Figure 2 (2)) used scaled connection nodes with curved edges. The scaled sizes were used to help represent the connection between two nodes while also maintaining the size distribution of input connection or output connection nodes within a supernode, by scaling the size of the nodes based on the smallest node size. The drawback of the scaled approach is that the scaled connection nodes from one sector cannot be compared to the scaled connection nodes from any other supernode or to the other set of connection nodes within the same supernode. This approach may also result in taller diagrams as any supernode that contains a node that is not at least the minimum size is increased by the minimum size multiplied by the number of either input or output connection nodes in the set containing the node that is not the minimum size.

The final design proposed (Figure 2 (3)) used uniform sized connection nodes with circuit diagram inspired edges. The circuit diagram approach was used to provide straighter edges that would use less of the space in the diagram. The drawback of the circuit diagram approach is that the edges are significantly close together and tracing these edges may be overwhelming without previous experience in circuit diagrams.

Expert Review

After finalizing the NEST diagram designs, the domain experts were presented the designs as a pilot study with a small subsample of the questions that were to appear in the user study. This was done to get feedback on our designs and to ensure that the questions that were being posed in the user study were representative of the high-level tasks identified previously. The feedback for the designs was positive and there was a large interest expressed in providing means of further exploration within the designs, mainly through the use of interaction and transitions. As the focus of this work was to validate our design, interactive exploration capability will be evaluated in future work.

EVALUATION

In order to evaluate the efficacy of the proposed designs, we performed a user study that explores the speed and accuracy for each task type in our taxonomy using the proposed visualization designs compared with a Sankey diagram. The data set from Greenberg et al.[6] was used to create our diagram designs as all of the data used in their diagrams was available, the data set was currently the best depiction of a multi-categorical data set used in a Sankey diagram, and the diagrams in Greenberg et al.[10] were manually created diagrams which could be considered a best-case representation of the data. K-means clustering was then performed on the number of non-zero nodes and the number of edges for each of the 26 states that we found to be consistent between the data and the given Sankey diagrams. Seven clusters in total were identified, with two of the clusters considered to be outliers. From the remaining five clusters, the state closest to the cluster center, Connecticut, Delaware, Nevada, Tennessee, and Wisconsin, were then used for the user study, with the outlier states, Vermont and Virginia, used for multi-diagram questions. Figure 3 shows an example of the generated NEST diagram for a state-level energy-water system.

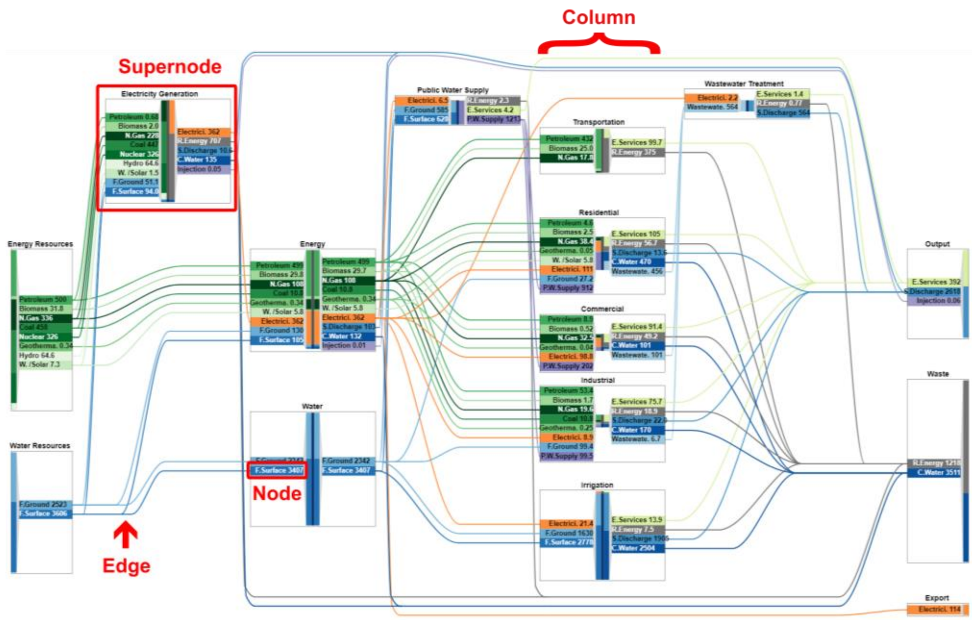

Figure 3. A sample NEST diagram representing a state-level energy-water system. This sample consists of 7 columns containing 15 supernodes that are connected by edges. The two hues represent the two different resource sectors, i.e., blue for water sector and green for energy sector. Exceptions are the orange nodes representing electricity that does not belong to both of the two sectors.

The questions for our user study were developed from our task taxonomy and our previous discussions with our domain experts. We proposed thirty questions, including five question for object identification, four for value retrieval, ten for link analysis, three for path analysis, three for pattern recognition and understanding, three for extremum identification, and two for inter-sector analysis. A larger number of questions were devoted to the first three task categories because these tasks were considered to be easier tasks that could be performed more quickly than the other four, and they were the task categories likely to be seen in other visualizations taxonomy works. A list of the example questions is listed in Table 1. The detailed study material, including questions and results, are included as supplemental material to this article.

Table 1. Examples of questions used in our user study based on different tasks.

Tasks	**Example Questions**
Object Identification	Is there ocean discharge from the water sector? **A**. Yes. **B**. No.
Value Retrieval	What is the total inflow of water to the Irrigation supernode? (Enter -1 if do not have an estimate)
Link Analysis	Which supernodes contribute to the Commercial supernode? (Select all that apply) **A**. Electricity Generation. **B**. Public Water Supply.
Path Analysis	Is it possible that any of the water in the Surface Discharge node is from the Fresh Surface node? **A**. Yes. **B**. No.
Pattern Recognition and Column Understanding	Sort the water resources by decreasing amount of usage. Which resource is in the 2nd position? **A**. Fresh Surface. **B**. Saline Surface. **C**. Fresh Ground. **D**. Saline Ground.

Extremum Identification	Which end-use supernode used the smallest, non-zero, amount of Fresh Ground water? **A**. Transportation. **B**. Residential. **C**. Commercial. **D**. Industrial. **E**. Irrigation.
Inter-sector Analysis	What is the total amount of water that is used for energy resource production? (Enter -1 if do not have an estimate)

Hypotheses

Prior to our study, we developed several hypotheses about the performance of NEST diagrams.

1. In terms of accuracy, the NEST diagrams could perform better in value-related subcategories including value retrieval, pattern recognition and column understanding, extremum identification, and inter-sector analysis. The NEST diagrams also contained nodes that presented a numeric value for the resource flow at intermediate stages in the diagrams which should make value retrieval, as well as pattern recognition and understanding, much quicker and more accurate.
2. When identifying maximum values, the NEST diagrams may require more time than a Sankey diagram since thick edges can be quickly captured. However, in Sankey diagrams there is always a unified minimum thickness for the edges with small values below a threshold, which makes it difficult in finding the smallest among them. Thus, our design should outperform Sankey diagrams in identifying minimum values.
3. The NEST diagrams would perform better in link analysis and path analysis. This was mainly due to edges being presented at a uniform size, which should be more easily traced, especially for small edges, from a source to destination than in a Sankey diagram. These characteristics should make link analysis and path analysis much simpler for diagrams with a large number of small edges.

Procedure

Participants: In total, we recruited 86 participants to participate in our user study through Amazon Mechanical Turk (MTurk). Each participant was paid $8 for their participation in the study which lasted approximately 50-60 minutes on average. As this user study was run through MTurk, there were no constraints placed on the computer hardware used by the participants during the study.

Training: Since Sankey diagrams may not widely be known and we were introducing new designs, an introduction page explaining the characteristics of both Sankey diagrams and NEST diagram designs was first presented to each of the participants. Three introduction pages, one for each NEST diagram, were used to present the specific characteristics of each of the designs. Only the introduction page corresponding to the participant's specific NEST diagram design was shown to the participant. On average, training lasted approximately 5-10 minutes.

Pretest: To verify that the users had a sufficient understanding of the material presented in the introduction, a screening quiz was given. In this quiz, we asked six questions, two simple questions with feedback and four more difficult questions without feedback. The first two questions were to allow the user to verify that they understood how the system worked as well as provide the opportunity to answer simple questions related to Sankey and NEST diagrams. The remaining four questions were to verify that the participant had sufficient understanding of Sankey and NEST diagrams. Participants were required to answer three of the four questions to continue with the full user study.

User Study: We presented each user with Sankey diagrams as well as only one of the proposed NEST designs. We consider the Sankey diagram to be the baseline, and we were mainly interested in how the proposed NEST diagrams compared to the Sankey diagrams, not to each other. Subjects were asked thirty unique questions, once for each of the two diagram designs, with the question ordering based on the order the categories are presented in the task taxonomy. The same question was asked once using one diagram followed by the same question for the other diagram, the ordering of the diagrams was randomly selected for each question. For each of the questions, states were pseudo-randomly selected from the five given states defined in the previous section for each question, where the state selected for the Sankey diagram could not match the state selected for the NEST diagram for the same unique question. As we did not consider the different states as having a significant impact on the ability to answer the questions, this was only needed to minimize the impact of presenting the same question twice in a row to the participant.

Design Preference: After answering the previous sixty questions, the participant was then presented with five questions asking about their preferred design and their perception of each of the diagrams in terms of accuracy and speed. These responses were not considered during the evaluation of the results as they only provide a person's preference, not an accurate means of quantifying their ability to use the diagram to solve problems.

Demographics: Finally, the participant was presented with an optional demographics survey to complete. Although the demographics information was also not considered in the results of this user study, it did provide an idea of domain areas that may be interested in similar work.

ANALYSIS AND RESULTS

Method

The goal of this study is to confirm if the proposed NEST designs are on par or better than the Sankey diagrams through two performance metrics namely, accuracy and time to finish a task. Accuracy is measured using the score of a participant for a specific question and was coded as 1 (for a correct answer) and 0 (for some or no correct answers). The accuracy and time metrics from 86 participants (30 participants assigned to design 1, 23 to design 2, and 33 to design 3) were analyzed using a generalized linear mixed modeling (GLMM) framework which produces the log-odds ratio between the Sankey diagram and each of the proposed NEST designs in both accuracy and response time. In this work, log-odds ratios are examined using a confidence interval of 95%.

Observations

With respect to the task categories, our NEST designs outperform the Sankey diagrams in both accuracy and response time for value retrieval and link analysis questions, indicating that the points in first hypothesis are confirmed. In extremum identification, our designs had higher accuracy but suffered from slightly longer response time, which matches the second hypothesis. In object identification and pattern recognition and column understanding, the differences are not significant in accuracy, while object identification questions exhibit shorter response time in our designs and exhibit somewhat longer response time in pattern recognition and column understanding. The primary takeaway from these results is the significant improvement in accuracy using the NEST designs in value retrieval, link analysis, extremum identification, and inter-sector analysis questions, and improvement in response time in object identification questions.

The main weakness of the NEST designs appears in the path analysis questions (20, 21, and 22), which is different from what we have expected in the third hypothesis. We consider the main reason for our lower accuracy performance here to be that in Sankey diagrams the flows are continuous from the beginning to the end, and thus less abstracted. However, in the NEST designs, the links are only between neighboring supernodes, i.e. there are no internal links representing connections between nodes in a supernode, which could cause difficulty comprehending continuous flows. Our results can be seen in Figures 4 and 5.

Statistically, because of the structure of our study, a definitive conclusion cannot be drawn about the superiority of any one of the NEST designs to the other NEST design alternatives as no participant was presented more than one of the NEST designs. As such, we focus our comparison of

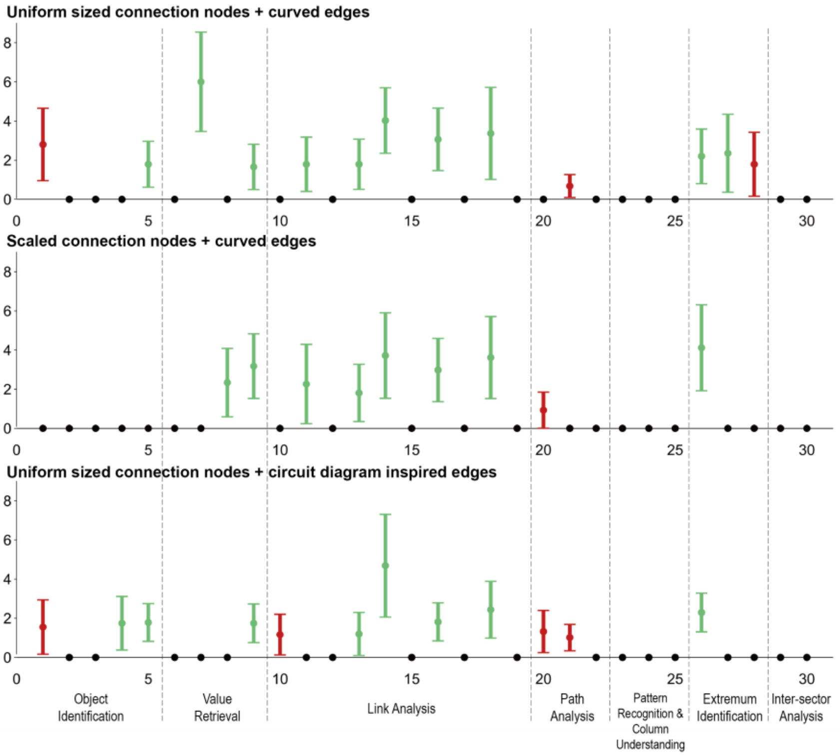

Figure 4. 95% confidence interval of the absolute value of log-odds ratio for accuracy. Red indicates better performance of Sankey diagram, green indicates better performance of NEST design, and black indicates no significant difference.

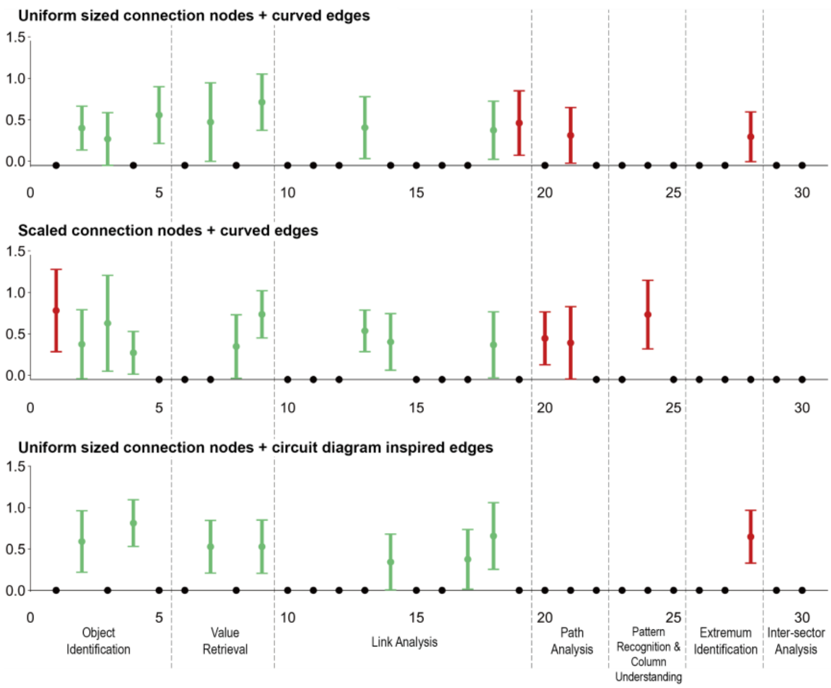

Figure 5. 95% confidence interval of the absolute value of log-odds ratio for response time. Red indicates better performance of Sankey diagram, green indicates better performance of NEST design, and black indicates no significant difference.

the NEST designs solely on the odds ratios obtained, which could also be affected by other characteristics of our experiment. From these results, the odds ratio for accuracy in design 2 is higher than for design 1 and design 3, suggesting that participants tend to answer correctly for design 2 more often than for design 1 and design 3 when compared to the Sankey. Due to the limitations of our study, we cannot state whether the difference between these odds ratios is significant. In terms of response time, the odds ratio for response time in design 3 is higher than for design 1 and design 2, suggesting that participants tend to answer more quickly for design 3 more often than for design 1 and design 2 when compared to the Sankey. Again, we cannot say that this is a significant difference. Ideally, accurate comprehension of the diagram should be more important than having a lower response time, from the odds ratio results, design 2 is our recommendation for visualizing heterogeneous data with directed flows.

CONCLUSIONS AND FUTURE WORK

Providing a means of visualizing multi-sectoral resource data is imperative to successful collaboration when examining the FEW nexus. In this work, we specify a set of visualization design requirements relating to Sankey diagrams for the FEW nexus, and a visualization approach, the NEST diagram, for multi-sectoral resource flows is developed. Our task taxonomy can serve as a basis for evaluation methods in this area. Without preserving the spatial understanding of the underlying structure of the data being presented, making sense of resource flows can be difficult for non-experts that are often the end users of these kind of diagrams. This work expands on these works to provide design requirements for heterogeneous data with directed flows, targeted at the FEW nexus, but applicable to other resource flow data as well.

We also present a diagram design (NEST) that has similar complexity to that of a Sankey diagram to handle the highly complex interactions that occur within the FEW nexus. Improvements to design aesthetics have been proposed by Breitkreutz et al.[5] and Alemasoom et al.,[2] but these works focus on improving the impact of edges on the understandability of the diagram, rather that examining more elaborate design elements that can capture the information that may otherwise be lost. Rather than focusing solely on how edges cross, the NEST designs seek to offer alternative design improvements that maintain the simplicity of the Sankey diagram, which is beneficial to non-expert understanding of the data being presented, and also provide more detailed information that may be necessary for expert analysis of the underlying data.

Although the design process was mainly a collaborative work with domain experts, our design demonstrated a relatively good performance for general users, based on the user study results. Overall impressions of the NEST designs were positive, and both domain experts and user study participants expressed interest in further work using these designs. Our future work will look to reduce the initial learning curve of our designs, identify user challenges in performing path analysis tasks, and define important interactions for the NEST diagram designs. Additionally, we will investigate the possibility of adding more features or custom visual elements specifically for domain experts, and integrate the NEST diagrams into a visual analytics system for increased data exploration capability. Furthermore, to tackle the issues stated at the end of the observations in the user study on differentiating three design choices, we will further justify the performance of three alternative designs with an in-depth comparative study.

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ABOUT THE AUTHORS

Brandon Mathis is a graduate student in the School of Computing, Informatics & Decision Systems Engineering at Arizona State University. His research interests include data visualization, computer vision, and machine learning. Contact him at bamathis@asu.edu.

Yuxin Ma is a Postdoctoral Research Associate in the School of Computing, Informatics & Decision Systems Engineering at Arizona State University. His research interests include information visualization, visual analytics, and visual data mining. Contact him at yuxinma@asu.edu.

Michelle Mancenido is an Assistant Professor of Statistics with the School of Mathematical and Natural Sciences, Arizona State University, Glendale, AZ, USA. Her expertise includes experimental design and statistical analysis of experimental data. Contact her at mvmancenido@asu.edu.

Ross Maciejewski is an Associate Professor with the School of Computing, Informatics & Decision Systems Engineering, Arizona State University, Tempe, AZ, USA. He was a recipient of the NSF CAREER Award in 2014. He has served on the organizing committee for the IEEE Conference on Visual Analytics Science and Technology and the IEEE/VGTC EuroVis Conference. Contact him at rmacieje@asu.edu.