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VISER: VISUALIZING SUPPLY CHAINS FOR ECO-CONSCIOUS REDESIGN

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ABSTRACT

In this paper, we present ViSER, an interactive visual analytics platform that visualizes supply chain data for enabling eco-conscious redesign. ViSER provides a visualization dashboard consisting of multiple mutually coordinated views that provide different perspectives on a particular supply chain scenario. Our platform allows users to visualize a change propagation metric associated with a particular redesign path. Hence, the user can balance the advantages of a redesign opportunity with the risk associated with its effect on the rest of the supply chain. Furthermore, ViSER offers lifecycle data representations that inform users' decisions particularly in the context of eco-conscious redesign. Coupling such environmental data with graph-based visualizations of product architecture, ViSER provides a novel decision platform for designers with a range of expertise levels. To demonstrate its utility, two use-case scenarios, from both a novice and expert perspective, are presented in detail.

1 INTRODUCTION

With future environmental regulations imminent in the United States, manufacturing companies are faced with the need to optimize existing product systems for environmental performance, something which often presents very difficult decision scenarios. The goal in such situations is to improve the environmental efficiency of the product system in question without compromising its performance, quality and deployment. The complexity of these scenarios is compounded once the entire supply chain is taken into consideration as other forms of meta-data are introduced, e.g. time to delivery per component and the demand of a particular retail stage. Even after conducting a full-fledged life cycle assessment (LCA), it is still difficult to identify hotspots for appropriate improvements, i.e. balancing cost and operational performance with environmental performance. Furthermore, interpreting a product system's environmental profile has been a significant challenge since the release of the ISO 14000 series [1], which within details standards associated with conducting a life cycle assessment. LCA has become the most accepted method for assessing the environmental impact of products, processes and systems. After an LCA is conducted, little direction is provided to the practitioner as to how to interpret the results and produce specific plans, courses of action or "jobs to be done" in order to improve the environmental efficiency of the system in mind. Many impact assessment methods, e.g. the Environmental Protection Agency's (EPA) Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), express environmental impact through different damage categories, essentially presenting a multi-criteria decision problem for the practitioner. In the case of TRACI, 12 different impact categories are reported and conducting tradeoffs between these criteria is quite difficult.

The inability of current LCA platforms and methodologies to properly inform redesign scenarios motivates this work. We use principles from the fields of visual analytics (VA) and information visualization (InfoVis), to develop an interactive visual analytics tool named ViSER that visualizes supply chain data for eco-conscious redesign. ViSER provides a visualization dash-

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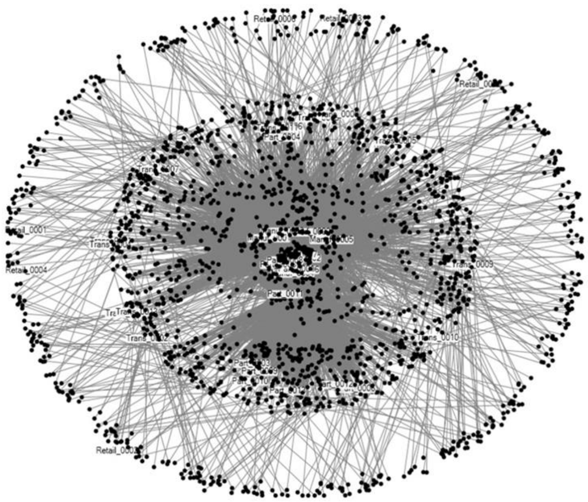

FIGURE 1. Example of a visualization of a supply chain using a graph layout offered by NodeXL [3]. This graph represents a supply chain of an aircraft engine [4] and is composed of 2,025 nodes and 16,225 edges, which demonstrates the complexity of product systems.

board consisting of multiple mutually coordinated views that provide different perspectives on a particular supply chain scenario. Our platform focuses on interpreting product-level attributes, e.g. LCA impacts, based on the structure of a supply chain and its product's architecture. To this end, ViSER offers dynamic visualizations of LCA data in multiple perspectives, allowing the user to discover anomalies and understand redesign implications. Fundamental to its method is the idea of engineering change propagation, a method for assessing the risk associated with redesigning a particular aspect of the product with respect to the entire system. In short, ViSER aims to contribute in lessening barriers associated with the interpretation stage of LCA, enabling pensive decision making for novices and experts.

Throughout the development of ViSER, we focused heavily on understanding the user's specific design tasks during the platform's use. This thinking is critical for the tool's success for a pool of users with a variety of expertise levels. For example, if junior engineers lack understanding of fundamental concepts or definitions related to environmental sustainability data, they will most likely be unable to overcome sufficient tradeoff scenarios between multiple criteria. Furthermore, there seems to be a tradeoff between software tool affordances and cognitive load [5]. The bridge between the two is significant in producing design tools that engineers with little training can properly use.

In this paper, we present the framework associated with the development of ViSER. Through ViSER, we claim that users can balance multiple criteria within a complex product system for creating effective redesign scenarios. First, the motivation and related work surrounding relevant areas of research is presented. The implementation of the ViSER system is then explained in detail, including a demonstration of the tool and its features. To conclude, we present two hypothetical use-case scenarios that reflect the utility of the tool for both novice and expert users.

2 MOTIVATION

Based on current challenges in eco-redesign, we introduce four requirements to be met within the ViSER framework:

R1: Exploring potential redesign scenarios,

R2: Extending environmental metrics to the system level,

R3: Weighing eco-related metrics against traditional criteria and

R4: Exploring alternative eco-impact weighting schemes.

With regards to R1, current computer-aided-design platforms offer retroactive features to help designers explore "what if" scenarios for downstream design modifications. In general, these tools over-simplify the redesign process by only allowing point substitutions, such as changing the material type, a single manufacturing process or the distribution mode of parts.

Furthermore, there is currently no widely accepted method for determining how such changes influence the product system and its supply chain. As a result, it is necessary to extend LCA metrics to meet the product system level needs, as stated in R2. Figure 1 shows an example of a supply chain network using NodeXL for the visualization platform [3, 4]. As one can see, some product supply chains are quite complex and dense. Their complexity is compounded since entity attributes depend on spatial, temporal and parametric constraints. Hence, there is a need for the development of more effective techniques to represent these graphs in the context of redesign planning.

Beyond the visualization needs for product systems, there still remain significant challenges in developing proper environmental metrics. As in R3, it is essential for these metrics to be comparable to traditional engineering criteria to ease tradeoff scenarios. Lifecycle impacts can be generally divided into five categories: (1) material extraction, (2) manufacturing and production, (3) distribution, usually dominated by transportation impacts, (4) the use phase of the system and (5) end of life activities, e.g. landfill and/or recycling [6]. For example, the majority of impacts associated with an automobile is within its use phase due to greenhouse gas emissions from combustion. If the goal is to reduce emissions by increasing fuel efficiency, decision makers might vie for lightweight materials, whose material extraction impacts are greater but help mitigate use phase effects. This tradeoff is only validated through another LCA, which is very resource (both cost and time) intensive. There is a need for platforms that ease this type of decision scenario.

As mentioned in the previous section, developing a weighting scheme for impact damage categories to aid in decision making is quite difficult. There have been considerable efforts to categorize damage categories into high level scores with weighting techniques. The issue is that these single scores are based on estimations and assumptions that frankly do not hold up when applying them outside of Europe. Software platforms that support LCA, e.g. SimaPro and GaBi, offer their own visualizations for reporting results, including single score metrics. However, these visualizations are static in nature and are difficult to adapt to specific practitioner needs. There is a strong need to develop a new weighting scheme paradigm (R4) that allows practitioners to interactively modify each weighting factor's contribution depending on the particular context.

3 RELATED WORK

Supply chains of product systems are quite complex since they carry temporal and spatial data in various forms. Traditionally, supply chains are represented as directed graphs or "netchains" [7]. These methods have led to the development of various criticality and complexity metrics to better understand such graphs. In situations where large complex and heterogeneous datasets are available, visual analytics has proven to alleviate user cognitive load and expedite useful discovery by projecting emergent relationships between entities [8]. However, representing redesign criticality metrics related to supply chains through visual interfaces is still in a nascent stage. The following sections review relevant literature related to understanding and communicating the underlying structure of supply chains. For this, we look at prevalent engineering metrics and visualization techniques associated with supply chain data.

3.1 Measuring complexity of supply chains

Complexity of supply chains can be measured but is not limited to the (1) *order of the system* taken as the number of elements or sub-systems, (2) *degree distributions* calculated using interaction or connectivity between the elements, sub-systems and the environment, (3) *causality or dependency* based on the dependency network in directed systems, (4) *heterogeneity* assessed by the variety, in types of elements, sub-systems and interactions, and (5) *degree of predictability and uncertainty* resulting from a risk assessment of the system. Of course, an effective metric would combine more than one of the listed supply chain attributes. However, procuring such information is often time and cost intensive creating a trade-off between metric accuracy and total project investment [9].

Dependency matrices have been used to develop complexity metrics within project management [10], supply chains [11] and manufacturing [12]. Even the theory of entropy has been used to understand the complexity of supply chains [13]. Within this project, a quantitative metric for supply chain complexity was formalized in order to ensure that the resulting framework is less subjective. One such dependency matrix, the design structure matrix (DSM), has been widely accepted as a way to measure the connectivity, modularity and complexity, among others, of product systems [14,15]. The DSM models structural relationships of complex systems, most often through binary relationships. Some extensions of DSM allow users to give qualitative weights to relationships in some form of low, medium, and strong degrees of correlation. Recent work has focused on proper visualization techniques for DSMs, i.e. through networks, matrices or a combination of both [16, 17]. Similar methods have been used to understand supplier network relationships through weighted adjacency matrices [18, 19, 20]. These efforts are from an operations research perspective and aim to measure static network attributes, such as resiliency.

Additionally, recent techniques have been developed to connect product complexity and supply chain impacts. Inman et al. (2013) [21] studied the probability of disrupting a supply chain by relating the likelihood of an individual part missing within a specific supplier. To the best of our knowledge, there are no published methods that assess the specific risk of introducing a design change and its associated impact on the supply chain.

3.2 Visualizing supply chains

Supply chains have been an application area of interest for the information visualization (InfoVis) community. An example of such work is representing supply chain interactions, e.g. cost trade-offs in production, within a causal loop diagram [22]. Recently, there has been a push to include geo-spatial data, e.g. through geographic information systems (GIS), in order to visualize supply chains across multiple dimensions [23]. Hu et al. (2010) [24] developed a framework for visually representing geographical attributes of a supply chain using a case study from the transport container industry. In another case study, Kassem et al. (2010) [25] developed a visualization scheme for mapping relevant information to the progress of constructing a building, including the supply chain.

Other work focuses on developing environments to aid decision making for supply chains. TISCSoft is a decision support tool to help optimize transportation infrastructure within a supply chain. Demand is shown by node sizing superimposed onto a map with specific distribution locations allowing the user to internalize multiple data entities at once [26]. Lin et al. (2000) [27] described IBM's efforts in representing traditional inventory management information in dynamic interfaces. Others have used similar ideas to improve the environmental sustainability of supply chains, e.g. towards innovation potential [28] and modeling carbon footprints [29]. MIT's Media Labs developed Sourcemap, a material-focused supply chain tool that allows the user to understand eco-costs per supplier [30]. Sourcemap does allow for material substitution, but lacks the capability of assessing the impact of redesigning a family of components or sub-assemblies. All of this work provides a benchmark for interactive environments with regards to visualizing supply chains. However, the connection between projecting design changes to supply networks seems to be missing.

3.3 Visually assessing change propagation

Although there exists a significant gap in research related to the impacts of design changes on a supply chain, there has been considerable work on change propagation through a product's architecture, commonly referred to as engineering change management (ECM) [31, 32, 33]. However, creating dynamic visualization interfaces that represent metrics within these efforts and, in turn, keeping the human user in the sense-making loop [34] is still in its infancy. Keller et al. (2006) [31] extended their widely accepted work in change propagation with a few prototype visualization interfaces for use in design [35].

Lessons can be learned beyond the domain of ECM. Goodwin et al. (2013) [36] developed a visualization tool for users to explore "what if" scenarios regarding their daily energy consumption in their homes. Another study investigated how using diagrams that show relationships between entities with a product development project enhance a design team's activities [37]. Each of these studies shows a form of change propagation by visually representing hypothetical situations back to users.

Contributions from the InfoVis and engineering design community seem to be separated in "silos" for this specific application. As of now, work in ECM does not well support human decision making since the algorithms used are far too automated and limit the human user's role in the sensemaking loop. Alternatively, efforts from the InfoVis community seem to be too focused on geospatial layout and do not display implications of supply chain changes to product architecture and vice versa.

4 THE ViSER SYSTEM

We introduce ViSER, an interactive VA platform that visualizes supply chain data for enabling eco-conscious redesign. ViSER provides a visualization dashboard consisting of multiple mutually coordinated views that provide different perspectives on a particular supply chain scenario. Figure 2 illustrates the general framework of ViSER, outlining its data representation platform. Essential to the process pipeline, the user interactively assesses visual representations that can be updated by naturally exploring the visualization interface. Based on user selection, product inventory data, i.e. material type, manufacturing processes and entity dependencies are fed to both the life cycle assessment model and the data representation model (DPM). Within the DPM, we implement several data related metrics to ease the sensemaking process: (1) a modularity index that defines sub-families within the supply chain graph, (2) a change propagation metric that represents connectivity within the product system and (3) contextual LCA data. These contribution directly relate to R2 and R3 described in the motivation section. This aligns with our goal of informing users as to which redesign options are most appropriate for improving environmental performance. If other redesign goals are proposed, this pipeline can be extended to handle other specific product attributes.

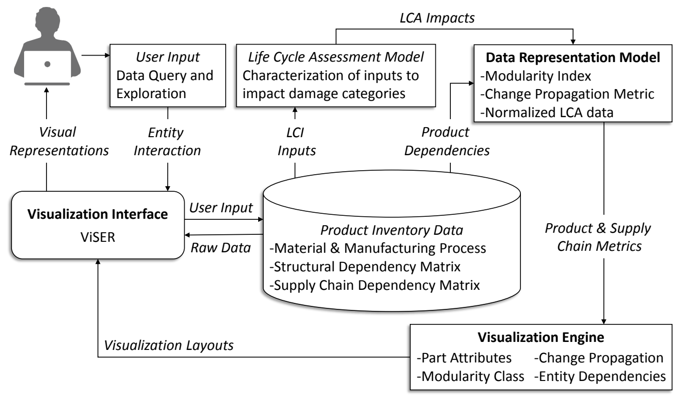

FIGURE 2. This diagram lays out the general pipeline of the data handling processes associated with the proposed visualization interface, ViSER. The user can query and explore entities by directly interacting with ViSER. Core components of the work presented here are shown in bold. The Data Representation Model implemented is fed by common product inventory data, commonly found in PDM systems, including material type, manufacturing processes and entity dependencies. In the case of eco-conscious redesign, we track environmental impacts using LCA. Once various metrics are calculated, the visualization engine feeds visual representations through ViSER then back to the user.

One significant contribution here is the mapping of the propagation associated with a redesign change in a component or subassembly through the supply chain. Assessing the risk associated with a product's architecture after an engineering change has been well studied as discussed above. Here, we use such work [31] as inspiration. However, it should be noted that to properly conduct a change propagation analysis, considerable knowledge of the product is required. Design knowledge of a product can be expressed via a product data management (PDM) system and a design structure matrix (DSM). Through a PDM system, the material and manufacturing attributes related to a product can be procured. Likewise, the DSM provides physical relationships between multiple components, essentially providing a product system graph in the form of an adjacency matrix.

4.1 Implementation Notes

This subsection discusses a prototype tool that implements the ViSER platform. This tool was built using Processing 2.1[1], a JAVA based open source programming platform that is designed to handle real-time user inputs through devices such as a mouse and keyboard. Furthermore, the potential of hosting ViSER on a web-supported architecture makes Processing an attractive prototyping platform. It is our hope that other practitioners and researchers from the community will use and contribute towards

[1] http://processing.org

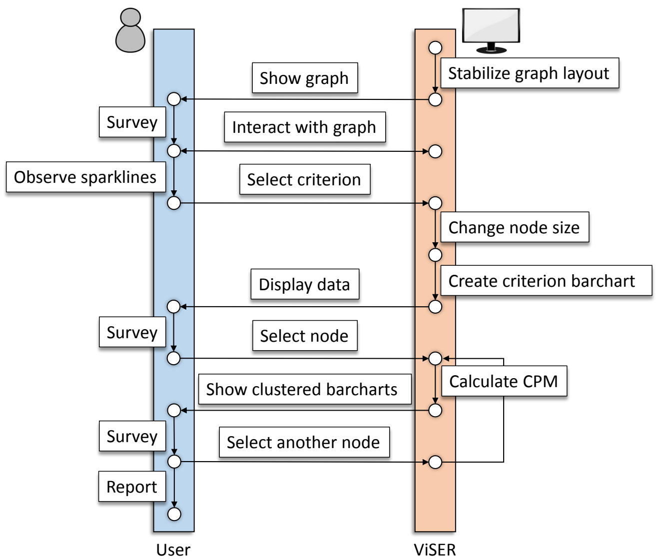

FIGURE 3. This represents an abstract prototype, describing a user-computer interaction pipeline. All tasks conducted by the user are shown in the blue rectangle, while internal processes by ViSER are shown in the orange rectangle. Specific interactions and their flows between the two media are outlined in detail.

ViSER allowing better dissemination of the platform. In our approach, graphs are used to visualize relationships between supply chains and its subsequent product graph. It is important to allow user interaction within the graphs themselves to handle large complex supply chains. Figure 3 details the proposed human-computer interaction with the prototype tool. The user's role, shown on the left, includes interacting with multiple visualizations of node attributes and the graph itself. ViSER tool, or the computer application, is designed to react with each command from the user. It should be noted that here, we propose using LCA data as node attribute data, since the nature of the data presents some interesting tradeoff as well as "what-if" scenarios. However, this general design can be used to visualize any data associated with a node in supply chains or product systems.

4.2 Visual features for supply chain entities

To meet R1, our tool allows for dynamic, quick surveying of node attributes in a user-centric manner. In general, the main cognitive anchor of the tool lies within the visual attributes of graphical nodes, including size, color and orientation. Each node-based feature and its intent is explained below.

- *Color*: The color of nodes (or entities) in the ViSER tool is based on a clustering algorithm described by Blondel et al. [38]. It offers additional coloring options based on stage type. For example, if the user wants to view only the transportation stages of the supply chain, the user can highlight the respective nodes by toggling a simple checkbox as seen in Figure 4.
- *Size:* Sizing of nodes is controlled to allow pre-attentive processing for specific criteria. When the user selects a particular criterion, the node size changes with respect to its value in that criterion. Additionally, the ViSER tool offers a feature in which the user can modify node size to reflect normalized values associated with an attribute.
- *Orientation:* The ViSER tool also allows for dynamic node placement, in which users can toggle a physics engine developed by Toxiclibs[2]. Therein, a force directed layout algorithm is implemented. Alternatively, the user can select a tree layout for the supply chain, which features a representation illustrating the parent-child relationships of all supply chain stages. For many instances, visualizing a tree structure for a supply chain is appropriate, especially with an acyclic graph.

Aside from displaying nodes according to specific attributes, all raw data associated with a node can be accessed via a tooltip that is generated on clicking that specific node.

4.3 Change propagation metric

Fundamental to ViSER is the expression of the change propagation for a selected redesign activity, as stated in R2. There are many such metrics present in literature which can be easily incorporated in the ViSER framework. For demonstration, we develop a simple metric, coined the change propagation index (CPI).The CPI is calculated by multiplying the adjacency matrix, a_{ij}, of the supply chain by its transpose and then summing each row except for the corresponding diagonal value, as shown below in Equations 1 and 2. It should be noted that the diagonal elements of A are omitted for the calculation of the connectivity metric because it represents the total number of connections between the i^{th} supply chain element and the other j elements.

$$A = a_{ij} * a_{ij}^T \tag{1}$$

$$CPI_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} (A_{ij}) \tag{2}$$

Additionally, in order to visualize connectivity of a particular node, the ViSER tool points to all neighboring nodes within a single hop by highlighting (in red) the edges associated with that particular node. This allows users to survey nodes of interest and quickly gain some insight into the system structure. Coupled with the tree layout visualization, this feature also provides a sense of pathways, in which multiple stages are strung together.

[2]http://toxiclibs.org

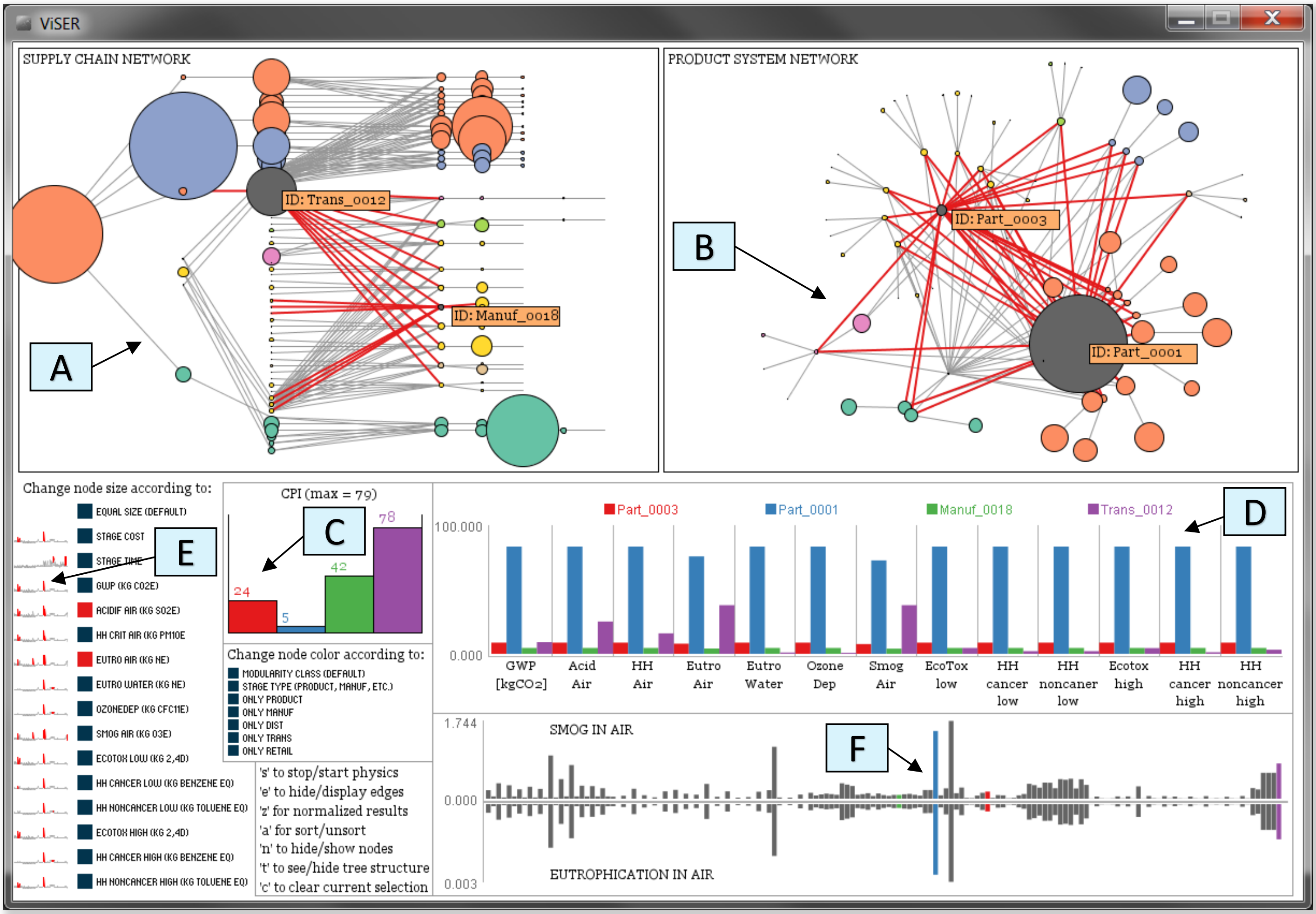

FIGURE 4. We present a screenshot of the ViSER tool. The supply chain shown is representative of the peripheral computer equipment industry. Each callout points to a specific feature of the ViSER platform and are described as follows: (A) a directed graph that represents the supply chain network as the edges connected to the selected nodes are shown in red, (B) a representation fo the product system graph oriented by a combination of force directed physics and user manipulation, (C) change propagation results for selected nodes of interest, (D) a comparison chart of impact categories for selected nodes of interest, (E) sparklines for each criterion with outliers shown in red and (F) the profile of selected node attributes, e.g. time and smog. A video demonstration of ViSER can be found here: http://youtu.be/pDJAqW9H3ME.

4.4 Visually comparing entity selections

Since one of the main goals of our platform is to compare different redesign alternatives, the ViSER tool offers multiple visualizations for node comparison. As a prototype tool we are limited to comparing single node selections. Future releases of the ViSER tool will allow multiple node and path selections. Each visualization illustrated in Figure 4 is reviewed below.

- *Sparklines:* Initial anomaly detection is done through surveying the sparklines [39] for each criterion, seen in Figure 4(E). Sparklines are small representations of all node values for a particular criterion, illustrating its relative range. In the proposed case study, values that exceed five times the average of all nodes are highlighted in red. Thus, when a significant portion of a sparkline is red, it suggests that a particular criterion could be of interest. The lower limit for this highlighting feature can be modified depending on context and domain.
- *Profile Barchart:* The profile barchart visually represents selected node values for ease of surveying. When two criteria are selected, the profile barchart splits into two adjacent charts, each representing one of the selected criteria. The profile chart is

sortable if the user deems appropriate, seen in Figure 5(M5). Otherwise, the bars are organized by an identification number in order to allow side by side comparison of two criteria for the same entity, as seen in Figure 4(F).

- *Clustered Barchart:* When two or more nodes are selected, a normalized barchart for multiple criteria is shown, as illustrated in Figure 4(B). This allows for direct comparison of multiple nodes across different criteria. The goal of this visual representation is to aid in multi-criteria decision making, such as in ranking several impact categories.

It should be noted that as the user hovers over a node, the ID label associated with that entity is shown on both graphs to provide an understanding of its role in both contexts. Furthermore, the edges directly connected to that node are shown in red to give a representative idea of the connectivity of that node. If the user clicks on the node, more specific information will be shown as a tooltip as well as live barchart comparisons for node selections. Issues regarding the interactivity of the tool were assessed via a case study, described in the following section. Observations here will lead to adjustments for future releases of the ViSER tool.

5 CASE STUDY

In order to demonstrate the utility of ViSER, we conducted a case study on a computer peripherals supply chain. The tested dataset was provided by Willems (2008) [4], which contains 38 real word supply chains released primarily for evaluating operations research related techniques. Here, we describe (1) the dataset used with necessary pre-processing work and (2) two use-case scenarios implemented in the ViSER tool.

5.1 Dataset details

Throughout this section, we are using a supply chain example that is representative of the peripheral computer equipment industry that was released openly at INFORMS 2008 [4]. This supply chain model was either created by company analysts or consultants with knowledge of the specific industry. The original dataset provides the connectivity of each node in the supply chain, along with the cost and time associated with each supply chain stage. The original dataset also provides information regarding the average demand at each retail stage. However, this was not taken into consideration here. Within each supply chain model, there are five entity types as defined by the source [4]:

- *Dist_:* a stage that distributes an item.
- *Manuf_:* a stage that manufactures or assembles an item.
- *Part_:* a stage that procures an item.
- *Retail_:* a stage that acts as a demand origination point.
- *Trans_:* a stage that transports an item between stages.

The specific supply chain model used in this study was chosen since it had reasonable complexity in terms of number of supply chain stages. However, the framework for which we present throughout this paper can be applied to any supply chain model that includes relationships between stages with minor modifications to input data.

5.2 Example: Peripheral Computer Equipment

The original dataset does not contain information regarding the corresponding product system graph (i.e. an adjacency matrix representing product structure relationships) associated with the supply chain. Hence, it was required to generate a synthetic product system graph that is representative of the actual adjacency matrix. The product system graph was generated by "short-circuiting" all manufacturing (that we assume to be representativeim of subassembly operations) and product stages. Though we cannot guarantee the accuracy of the generated product system graph, we can argue that the resultant graph still illustrates the utility of the tool by observing user interaction with the data.

Ideally, product information would be available in order to conduct a detailed life cycle assessment (LCA), in which each component is assessed based on its material, corresponding manufacturing processes and transportation details. As we do not have access to this information, we conducted an economic input-output LCA (EIO-LCA) using the web-tool from Carnegie Melon University[3]. Using EIO-LCA, we estimated environmental impacts associated with the cost of each stage in the supply chain. Since the impacts are calculated based on a dollar value, many of the entity attributes related to environmental impact directly scale with their cost. A more detailed LCA would most likely, pose more complex and interesting tradeoff scenarios.

5.3 Use-case Scenarios

In this section, we present two use-case scenarios to demonstrate the usefulness of the ViSER tool. Within the use-case scenarios, we present hypothetical users and their stories as they would use our tool. Within the scenarios, we argue that our tool can be used to produce (1) visualizations for reporting general life cycle assessment data (centered for novice users) and (2) dynamic sense-making of multi-criteria environmental data (targeted at expert users). Both user interaction flows are shown in Figure 5. It should be noted that developing these use-case scenarios and demonstrating how a user can recognize a specific part as the best candidate for redesign can validate the usefulness of the tool. However, in order to assess the utility and ease-of-use of the tool, a full user study is required.

5.3.1 Novice user.

Bart is a junior engineer at a computer casing manufacturer. He is asked by his manager to organize findings by a third party LCA practitioner to report potential redesign scenarios for a product. Bart has little understanding of impact categories, but has experience in balancing more tradi-

[3] http://www.eiolca.net/

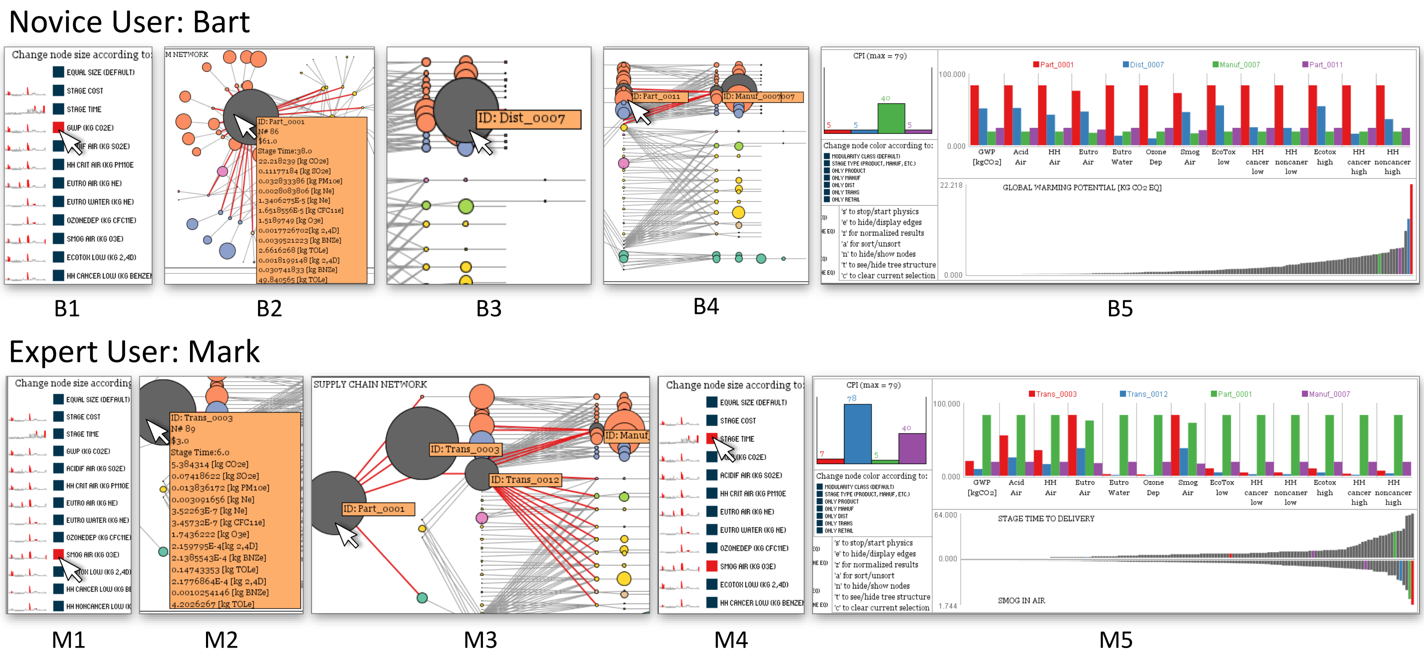

FIGURE 5. For the two use-case scenarios, each working flow in ViSER is presented through a step-by-step process. As a novice user, Bart (B1) chooses GWP as the criterion of interest via a checkbox, (B2) surveys entity attributes via a tooltip, (B3) explores entities with significant contributions to GWP, (B4) decides on final selections, and (B5) visualizes reported outcomes. As an expert user, Mark (M1) selects a criterion based on its distribution represented by the sparklines, (M2) surveys entity attributes via a tooltip, (M3) decides on final selections, (M4) selects an additional criterion of interest and (M5) visualizes reported outcomes.

tional engineering criteria, e.g. cost against mechanical performance. Most of Bart's understanding of environmental performance is garnered by actively watching national news outlets on topics related to climate change and greenhouse gas emissions. Bart launches the ViSER tool in order to first survey how the structure of the supply chain relates to the product graph.

Bart is asked to indicate what specific path or module within the supply chain needs most attention. As a result, he uses the default setting for which supply chain entities are colored based on modularity class. Bart then changes the size of the nodes to be representative of their impacts associated with global warming potential (GWP) as shown in Figure 5(B1). As someone with little expertise in dealing with multiple environmental impact categories at once, he chooses GWP since greenhouse gas emissions are a particular focal point of his project team in order to mitigate the product system's total ecological footprint. He quickly notices that the orange colored module seems to have the highest impact relative to other sub-families within the current design. Bart then selects the largest contributing entity, Part_0001, and surveys all product attributes via the tooltip, shown in Figure 5(B2). Bart continues to select the second highest contributing stage to GWP, Dist_0007 (Figure 5(B3)). Across this path exist other significant stages, including Part_0011 and Manuf_0007 which happen to be the fifth and twelfth most contributing stages to GWP, respectively. After selecting the rest of the path (Figure 5(B4)), he is able to visualize these ranks by surveying the sorted barchart at the bottom of ViSER's field (Figure 5(B5)). He deems this pathway to be highly desirable for a redesign scenario. Bart records this pathway and reports back to his superiors.

5.3.2 Expert user.

Mark is a project manager at a computer casing manufacturer with extensive experience as an LCA interpreter and practitioner. In other words, Mark can balance the performance of a product among several environmental damage categories. Mark is asked by upper management to report on the environmental hotspots associated with the product, so that his company can be positioned better for imminent regulations. The bottom row of Figure 5 reflects Mark's use of ViSER. Here, Mark first selects a specific damage category of interest based on anomaly detection using the sparklines (Fig. 4(E)), i.e. smog in air, as seen in Figure 5(M1). The size of each node is reflective of the normalized magnitude compared with the maximum value of the damage category of interest, in this case, smog. The profile of that damage category is given at the bottom of the interface, similar to Figure 4(F). Next, similar to Bart, Mark surveys the highest contributor to smog using the tooltip feature in Figure 5(M2). Mark then continues and selects 4 different nodes as candidates for redesign. Trans_0003, Trans_0012, Part_0001, and Manuf_007 are the supply stages chosen and their data is shown in red, blue, green and violet, respectively. The color codes are consistent throughout all resulting visualizations.

Interested in how these product entities perform in time to delivery, Mark selects stage time as another critical attribute (Figure 5(M4)), the profile barchart now reflects both criteria. Mark then makes final selections for candidates. As an overview, Mark is able to visualize a comparison bar chart across each impact category of all selections, shown in Figure 5(M5). Additionally, change propagation metrics for each selected nodes. Mark surveys each metric using the color-matching scheme per selection.

This case illustrates an interesting tradeoff scenario. Here, smog is highlighted as the most important damage category. Trans0002, shown in red, produces the most smog compared with all other stages. Mark understands this scenario by simply surveying the node diameters. However, since Part_0001 has a lower change propagation score and exhibits a higher potential gain across other damage categories, Part_0001 seems to be the best candidate for redesign. Mark takes note of the findings and presents the final visualization as seen in Figure 5(M5).

6 CONCLUSIONS AND FUTURE WORK

In this paper, we have presented ViSER, a novel visual analytics platform for selecting appropriate supply chain entities for redesign. ViSER takes advantage of existing visualization techniques to create a user-centric environment to aid multi-criteria decision making. A case study of a supply chain representative of computer peripheral equipment was used to demonstrate the usefulness of ViSER tool: a prototype implementation of our framework. The ViSER tool enables users' to identify redesign activities that minimize total environmental impact. Within this case study, we also explored two potential use case scenarios of our framework. Additionally, ViSER presents a possible solution for the interpretation of life cycle assessment data of complex supply chains with multiple damage categories. To the authors' knowledge, there is no benchmark yet accepted in the research community to handle the interpretation stage of LCA.

Besides improving the interface of the ViSER tool, we plan to incorporate several enhancements to the presented visualizations. First, we plan to include additional performance criteria such as cost and time in the change propagation index. This would be a first step in understanding the percent degradation of the system after making a proposed change (aligning with goals outlined in R3). Next, we plan to enhance user interaction with bar charts, e.g. allow user to highlight nodes by selecting their bar chart contributions. This type of interaction will provide another option in how specific entities are chosen. Since an objective of this project is to provide a design tool that aids in the interpretation stage of LCA, we can set a new paradigm for LCA categorical weights. A user-centric approach would allow the practitioner to choose multiple weighting schemes based on global standards and adjust or tune the weights specific to their situation as stated in R4. This perspective has not been well studied and would provide an interesting viewpoint for improving LCA.

Additionally, we plan to validate the presented software prototype through targeted user studies. We plan to recruit experts in both the domains of product system design and life cycle analysis in order to more deeply understand users' cognitive flow while using ViSER. Therein, we plan to implement qualitative analysis to asses the tool's viability. This will not only suggest specific improvements to our framework but will hopefully present additional research initiatives in the newly focused area of visual analytics applied to engineering design.

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