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DESIGN PATTERNS FOR VISUALIZATION-BASED TOOLS IN SUSTAINABLE PRODUCT DESIGN

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ABSTRACT

Most design activities involve exploring and comparing existing designs. Thus, adopting an eco-conscious approach in the design exploration process can aid environmentally sustainable product design (SPD). One approach for supporting exploration in SPD is through tools based on information visualization (InfoVis). The use of InfoVis for SPD allows data-driven exploration of solutions that is rapid, direct, and supports investigation of questions that the designer may not have identified. Previous work has demonstrated the utility of InfoVis tools for different facets of the lifecycle, e.g. redesign, supply chain exploration, and life cycle assessment. These tools focus on projecting sustainability-related implications back to design. However, to fully realize their potential, future tools must synthesize data in a manner that helps designers view the effects of a design change on all downstream stages. Such tools will have to work across multiple data types, visual representations, and stakeholders. In this paper, we take the first steps towards addressing this challenge by formulating design patterns for visualization and interaction of product lifecycle data. These design patterns were synthesized by reviewing previous works that have successfully created visualization-based tools for SPD. The suggested design patterns can, (1) serve as a guide for creating integrated visualization-based tools for SPD, and (2) help create reusable visual components that aid in quick interface wireframing.

1 INTRODUCTION

Reducing the environmental (env) impacts of products has become an important focus for industries [1]. Among the opportunities available for reducing the env. impact of a product, usually the design stage offers the most potential [2]. Integrating env. aspects of a product with its design creates the need for searching env. information, performing env. assessments, and outlining a suitable strategy [3]. In this paper, we focus on the *search* part of this process and look at visualization-based tools for exploration. The use of visualization-based tools in sustainable product design (SPD) is designer-driven and often involves exploring previous designs to

- compare env impacts of design alternatives,
- support discovery of more benign design alternatives, and
- aid designers' understanding of correlations between design attributes and env. impacts for a single or a set of designs.

These activities are critical for supporting SPD, as quantitatively predicting a product's lifecycle env. impact based on its design
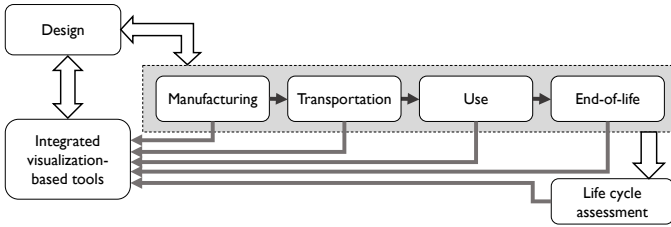
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FIGURE 1: ROLE OF INTEGRATED VISUALIZATION-BASED TOOLS FOR SPD. THE GOAL IS TO ALLOW DESIGNERS TO PERFORM DATA-DRIVEN ANALYSES OF IMPLICATIONS IN DOWNSTREAM STAGES RESULTING FROM DESIGN CHANGES. PRODUCT LIFECYCLE DATA FROM DOWNSTREAM STAGES AND RESULTS FROM ENVIRONMENTAL ASSESSMENT TOOLS (E.G. LCA) ARE PROJECTED BACK TO DESIGN THROUGH THESE TOOLS.

attributes is a prohibitively challenging task [4]. Our literature review revealed that current visualization-based tools are often developed to inform designers about the sustainability-related implications of specific facets of the lifecycle. While such tools project valuable information back to design, the effective use of such tools requires researchers to explore methods for holistic integration of data from all downstream stages [2]. To make use of lifecycle data effectively, future tools must synthesize data in a manner that helps designers view the effect of making a design change on all downstream stages. Such tools will work have to work across multiple data types, visual representations, and stakeholders. Figure 1 shows this integration layer that can allow designers to perform data-driven analyses of design changes in downstream stages. Lifecycle data from downstream stages and results from env. assessment tools, such as life cycle assessment (LCA), are projected back to design through the use of integrated visualization-based tools. These tools should support *human sensemaking* using both (1) data-driven methods that gather, process, and summarize data, and (2) user-driven methods that allow users to input their domain knowledge or data-driven insights during exploration. The need for a human-in-the-loop is critical as SPD involves tasks wherein, although the goal is known, designers rarely know the best approach for the problem, what questions to ask, and which among them are the right questions to consider [5]. Furthermore, ambiguities present in design representations, lack of information from downstream stages, and uncertainties in env. assessment all increase complexity in the SPD process [2].

In this paper, we take the first steps towards creating integrated visualization-based tools for SPD by formulating design patterns for visualization and interaction with regards to lifecycle data. For this, we adopt an inductive line of research [6] and derive these patterns by reviewing previous research that has successfully created visualization-based tools for SPD. Synthesizing a list of design patterns for visualization-focused tools in SPD is essential for reducing the barrier to their creation for both academic researchers and industry practitioners. Design patterns

provide a tested heuristic for quick prototyping, reducing the cost of creating future tools. This is particularly significant in SPD as the growing complexity of production, consumption, and environmental systems necessitates flexible, usable, knowledge management tools that can integrate information across the lifecycle.

2 MOTIVATION FOR USING INFOVIS TOOLS IN SPD

Considering sustainability adds parameters and constraints to the design process, which increases complexity [7]. In SPD, the challenge of dealing with multiple inter-related parameters is compounded by the fact that methods and computer support tools for SPD are disconnected from those focused on design exploration. One primary reason for this disconnect is the mismatch in data representations used in these two contexts [8]. To illustrate, conducting an LCA for a part does not require knowledge about its form (shape), fit (tolerances), or function. However, these attributes are vital for assessing design intent. Reducing such gaps is essential for easing the disconnect between tools for design exploration and SPD.

Fully and semi-automated approaches based on techniques, such as neural networks and expert systems have been previously applied to SPD [9, 10, 11]. However, it is challenging to extend them towards exploration-focused tasks primarily due to its ill-defined nature. Previous research (see Section 4) has shown that InfoVis—the use of computer-supported, interactive, visual representations of abstract data to amplify cognition [12]—offers strong potential to support exploration tasks in SPD. Visualization-based tools combine the powerful pattern detection properties of the human visual system with the large data processing and manipulation capabilities of a computer system [13]. This allows visualization-based tools to support designers' insight generation processes and leverage their expertise in qualitative decision-making. An important aspect of InfoVis is keeping the human in the decision loop. This makes InfoVis-based techniques relevant towards tasks in SPD, which are largely open-ended. Another advantage of using InfoVis tools in SPD is the ability to create a common representation between domains (in our case environmental assessment and design exploration) by transforming data into graphical primitives [14].

3 NOMENCLATURE

Here, we define a *designer* as a person who is involved with the generation and development of ideas that leads to a new product [15]. On the other hand, we use the words, *researchers* and *practitioners*, to denote people in academia and industry, respectively, who are interested in creating new visualization-based tools for *designers*. *Design patterns* refer to reusable implementation or solution strategies that can be customized to address challenges in a specific context. Originally published for object-oriented programming [16], design patterns have been successfully used in codifying solution strategies and best prac-

tices in the context of information visualizations [17,18]. We use Shneiderman's task-by-type taxonomy [19] to categorize previous tools, and denote InfoVis tasks in this taxonomy by *T#*. The symbol *P#* is used for denoting the synthesized design patterns.

4 RELATED WORK

Creating InfoVis-based tools for SPD requires an understanding of visual representations for both design and sustainability-related data. These representations should be situated in an overall framework that allows designers to explore the design space. Most previous works on supporting design exploration in the context of env. sustainability usually focus on developing env. indices useful for the exploration process. There seems to be a research gap on methods and tools that support human-centered exploration for SPD. To understand barriers in this context, we review previous works that (1) develop computer-aided methods and tools for enabling SPD, (2) apply InfoVis techniques for aiding design exploration, and (3) promote env. sustainability through InfoVis.

4.1 Methods and tools for sustainable product design

Most design activities involve the reuse of existing design information to create new designs. Thus, supporting exploration of more benign alternatives in a design space (or repository) presents a significant opportunity for promoting SPD. Previous research in this area has looked at methods and tools for estimating env. performance of existing designs using neural networks [9,10], simplified life cycle indices [20,21], and function-based relationships [22,23]. A majority of these papers focus on estimating env. indicators relevant to the context of application. Even though such methods have been successful in facilitating reuse of design information, most of these methods cannot be extended towards interactive exploration of design spaces. There is a significant lack of research on understanding differences in representations between design data and sustainability-related data from the standpoint of the designer. The disconnect in data representations translates to a reduction in the effectiveness of env. assessment tools for design. In their research project with industrial designers, Lofthouse [24] identified that eco-design tools, such as the LIDS wheel and the EcoReDesign programme, were incongruous to the design process. Similarly, Rio et al. [8] highlight challenges related to data interoperability between env. assessment and product design. In response to these challenges, researchers have proposed expert systems [11] that provide sustainability-related recommendations in early-phase design. Other approaches (see Section 4.3) propose the use of InfoVis as a means to commonize representations in design and sustainability assessment.

4.2 Visualization-based tools for design exploration

Within engineering design, visualization finds application in both scientific visualization (SciVis) and InfoVis. Card et al. [12]

differentiate the two methods in that SciVis is typically applied to scientific/physically based data (e.g. engineering stress and fluid velocity) while InfoVis is directed towards abstract, non-physically based data (e.g. parameter spaces and product/supply chain structures). Design spaces usually contain non-physical data without a prescriptive mapping to visual representations. This makes the study of InfoVis for design exploration a research discipline in its own right. The use of InfoVis in design exploration is predominantly driven by the need to (1) characterize and navigate multi-dimensional design spaces [25], (2) understand parameter trade-offs for design optimization [26, 27], and (3) generate insights, patterns, and trends for design decision-making [28, 29]. Most InfoVis applications in design exploration relate to situations wherein the designer is exploring multi-dimensional datasets with limited knowledge about the relationships in the data. Unlike traditional data exploration, visual exploration using InfoVis requires users to interact with abstract data representations. A range of standard and custom visualization methods have been utilized in previous work to support exploration processes. Interested readers are directed to works by Chi [30] and Keim [31] that present taxonomies for commonly used data visualization techniques. InfoVis-based tools in SPD often rely on such visualization techniques to relate metrics from env. assessment to design parameters.

4.3 Visualization-based tools for sustainability

Previous efforts integrating visualization and env. sustainability has been directed towards, (1) *eco-visualization:* the use of visualization to promote sustainable behavior in end-users, and (2) *visualization for aiding sustainable product design*: the use of InfoVis to support designers practicing SPD. Eco-visualizations have been explored to provide eco-feedback on energy consumption, carbon loads, water usage, and waste recycling [32, 33]. They have also been used for, promoting conservation-related dialogs among community members in the context of paper printing [34], and for developing persuasive media that promote eco-conscious behavior [35]. Along similar lines, Lilley [36] present a list of attributes for *behavior changing* devices. These attributes can be adapted for developing eco-visualizations that promote sustainable behaviors in end-users.

Creating information visualizations for the designer presents a different set of challenges when compared to designing eco-visualizations for the end-user. The primary reason is that information visualizations for designers focus on supporting insight generation through interactive exploration of design variables and performance/output parameters. On the other hand, visualization for end-users often tend to focus on providing feedback only on performance/output parameters (i.e. energy efficiency and transportation impacts). Contextualizing visualizations to the design process adds additional parameters (and dimensions) making insight generation quite challenging. Studying mechanical designers, Bernstein et al. [7] discovered that vi-

sual representations that interface LCA with design are necessary for promoting SPD. By translating design and env. sustainability variables into graphical primitives, visualization-based methods enable concurrent presentation of data and support designers' insight into the generation processes.

Espinosa et al. [37] present a technique for generating data visualizations useful for env. LCA. The authors develop VisEIO-LCA, a tool that can visualize product-related env. data. Otto et al. [38] use a glyph-based information representation and visualization approach to represent lifecycle information. The authors generate multiple visualizations for analyzing LCA results of a desktop computer. Ramanujan et al. [39] propose a framework, and a multi-dimensional visualization tool that allows exploration of 3D model repositories. The tool helps the designer explore part repositories driven by similarities in design attributes (i.e. material, manufacturing, and function) while simultaneously considering the env. implications of a chosen design. A mutually co-ordinated visualization tool for simultaneous exploring supply chain and design data in the context of eco-conscious redesign is described by Bernstein et al. [40].

Although there are several commercial tools that support SPD [41], only a handful of them use interactive data visualizations that allow users to explore the decision space. A notable exception is SourceMap, a tool for visualizing env. indicators for a product's supply chain [42]. SourceMap represents supply chain data as node-link diagrams that are overlaid on geographical maps. Apart from the works discussed above, other researchers [43, 44, 45, 46, 47, 48] have also looked at visualization techniques for product design and env. assessment.

5 METHODOLOGY

To identify visualization-based tools in SPD, we conducted a review of previous literature. We identified previous works through Google Scholar, Scopus, Science Direct, and the ASME Digital Collection using combinations of the following SPD and visualization related keywords: {*sustainable design*, *sustainable product design*} and {*information visualization*, *visual analytics*, *visual exploration*}. We filtered the resulting papers based on, (1) relevance to sustainable product design, (2) presence of a visualization-based tool in the paper. Additionally, if we found multiple papers by the authors that discuss the same concepts, we opted to include the most comprehensive version of those paper in the review. Table 1 lists papers that were selected from the search process. We included QuestVis [49] as the discussions herein are valuable for visualizing env. indicators.

We used Shneiderman's task-by-type taxonomy (TTT) [19] to infer design patterns from the tools that were reviewed. The TTT consists of 7 InfoVis task-types (overview, zoom, filter, details on demand, relate, history, & extract) for creating visual analysis tools. We used the TTT over other taxonomies present in InfoVis literature since (1) it forms one of the fundamental

TABLE 1: LIST OF VISUALIZATION-BASED TOOLS IN SPD RE-VIEWED TO IDENTIFY DESIGN PATTERNS. FOR EACH TOOL, REL-EVANT TASKS-TYPES FROM THE TTT ARE ALSO SHOWN.

Name	Supported Activities	Illustrated Tasks
shapeSIFT [39]	Exploration of 3D part repositories	overview, filter
VisEIO-LCA [37]	EIO-LCA results visualization	zoom, details on demand
OM-Glyphs [38]	LCA & LCIA results visualization	extract
QuestVis [49]	Policy making & Indicator visualization	zoom, filter, history, extract
ViSER [40]	Concurrent exploration of supply chain and product architecture	details on demand, relate, extract
SourceMap [50]	Supply chain visualization and analytics	overview, zoom, details on demand
Uchil & Chakrabarti [45]	Interfacing LCA results with product design	filter, relate
i-Tree [46]	Transformation of impactful LCA flows to eco-potentials	zoom, filter, relate

basis for more recent works on InfoVis taxonomies, and (2) a task-based classification allows us to extract design patterns that can map to high-level features that can be implemented in an interface. The latter is significant as low-level implementations used by researchers and practitioners are strongly influenced by the context for which their tools are built. Therefore, providing guidance for low-level implementations (such as the kind of visual representation or software to use) might be overly constraining. Table 1 shows the corresponding TTT principles that are embodied in the tools that we reviewed.

6 MAPPING THE TASK-BY-TYPE TAXONOMY TO VISUALIZATION-BASED TOOLS IN SPD

For each task type in the TTT, (1) we provide examples of their usage based on works in Table 1, and (2) infer design patterns for InfoVis-based tools in SPD relevant to this task-type.

6.1 Overview (T1): Obtain overview of design space

Overviews are intended to provide a macro-level perspective about decision spaces. Good information visualizations, according to Shneiderman, follow the mantra: *Overview first, zoom and filter, then details on demand* [19]. In the context of SPD, overviews can be used for (1) showing variations in env. indicators or design parameters over a collection of designs, (2) presenting a global perspective of a system across specific dimensions (i.e. geographical overlays, calendar charts), and (3) visu-
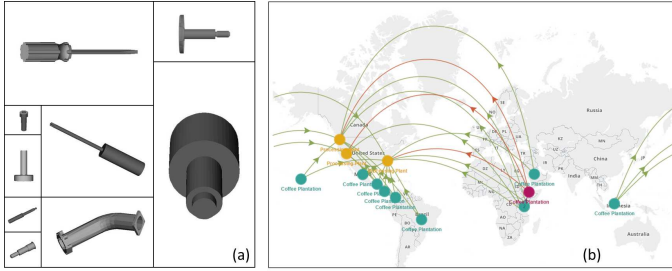
FIGURE 2: (A) THE SHAPESIFT PROTOTYPE [39] PROVIDES AN OVERVIEW OF PART ALTERNATIVES USING A SQUARIFIED LAYOUT VISUALIZATION. HERE, THE AREA OF EACH CELL IS SCALED INVERSELY TO THE ENVIRONMENTAL INDICATOR OF THE CORRESPONDING PART. (B) AN OVERVIEW OF A SUPPLY CHAIN FOR A PRODUCT IS SHOWN USING A GEOGRAPHICAL MAP IN SOURCEMAP [50].

alizing the overall structure of the design/decision space.

6.1.1 Illustrative examples in SPD

shapeSIFT: The shapeSIFT tool (Fig. 2(a)), uses a squarified layout for visualizing a set of similar shaped parts obtained from sketch-based retrieval. Here, the env. indicator (cumulative energy demand per unit volume) is mapped to cell size. Relevant design parameters like material, manufacturing, and function are encoded using secondary variables, e.g. color.

Sourcemap: An overview of the geographic location of each supply chain node, is presented on a map overlay in Sourcemap (see Fig. 2(b)). In the context of SPD, such overlays help in understanding env. indicators such as carbon footprint resulting from transporting goods/services across geographies. Sourcemap allows designers to easily identify hotspots for improvement and realize alternative supply chains that are both economically viable as well as more environmentally benign [42].

6.1.2 Suggested design patterns

Visual overviews are useful in providing a *lay of the land* so that designers can gauge properties for the entire or a significant portion of the design space. Based on the design of shapeSIFT and SourceMap, we infer the following design patterns for SPD.

P1: *Indicator overviews:* Visual presentation of an overview for env. indicators allows designers to make quantitative and/or qualitative comparisons across design alternatives. Interactions such as sorting and filtering of overviews benefit designers in quickly characterizing the exploration space [51].

P2: *Eco-prominence:* env. indicators can be represented using the most prominent visual variable on that visualization. When possible, visual variables for env. indicators should allow pre-attentive processing of information [52].

P3: *Eco-persistence:* Persistent visualizations of env. indicators help designers understand the env. performance of design
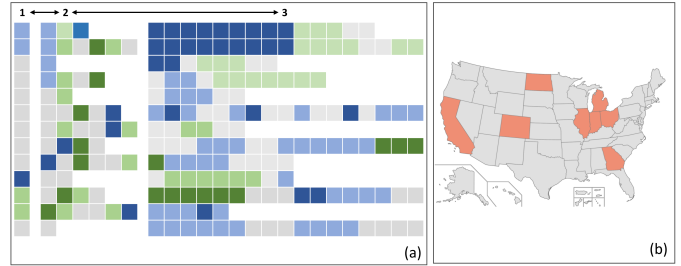

FIGURE 3: (A) MULTILEVEL INDICATOR BROWSING SUPPORTED IN THE QUESTVIS INTERFACE [49]. THREE AGGREGATION LEVELS OF OUTPUT INDICATORS ARE ACCESSIBLE TO USERS. COLOR ENCODES THE MAGNITUDE OF CHANGE IN AN INDICATOR. (B) ILLUSTRATION OF A GEOGRAPHICAL OVERVIEW IN VISEIO-LCA [37]. USERS CAN ZOOM INTO IMPACTED REGIONS (IN RED) AND GATHER DETAILS.

spaces. In visualizations that overlay env. and other design data, visual variables coding env. indicators should remain persistent through view transformations.

6.2 Zoom (T2): Zoom in on items of interest

Zooming is an interaction technique for narrowing the search or decision space by changing the magnification level of the visualization. Methods for zooming include (1) *geometric zoom*, where object sizes are visually magnified, and (2) *semantic zoom*, where the size and/or context of the object changes in relation to the information being presented [53]. In the context of SPD, zooming can be useful in controlling the level-of-detail for aggregated data such as env. indicators [49], and for increasing magnification to provide additional detail [37].

6.2.1 Illustrative examples in SPD

QuestVis: This interface enables multilevel indicator browsing using expandable color-encoded boxes (Fig. 3(a)). Three levels of magnification are accessible, including (1) a top level showing aggregate values for each of the 13 categories, (2) an intermediate level showing the most important indicators in a specific category, and (3) the lowest level showing all 294 output indicators across 13 categories. QuestVis preserves transparency of the aggregation process by allowing users to zoom into details. Another advantage of multilevel indicator browsing is that the overview visualization uses very little screen space, and allows users to easily compare indicators across different scenarios.

VisEIO-LCA, SourceMap: VisEIO-LCA and Sourcemap use geographical overlays. In VisEIO-LCA, a geographic map visualizes locations affected by env. impacts (Fig. 3(b)). Users can magnify the displayed map to access more detailed information about specific regions. Similarly, SourceMap uses pan+zoom interaction for navigating multiscale geospatial datasets.

i-Tree: The i-Tree uses a multi-level approach for products and processes to analyze complex inventories. The highest level
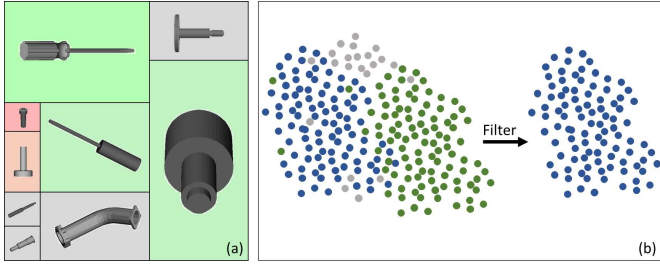
FIGURE 4: (A) SHAPESIFT [39] ALLOWS USERS TO FILTER RESULTS BASED ON SIMILARITIES IN MATERIAL, MANUFACTURING, AND FUNCTION. ALTERNATIVES THAT ARE FILTERED OUT ARE GRAYED IN THE SQUARIFIED LAYOUT VISUALIZATION. (B) QUESTVIS [49] ALLOWS USERS TO FILTER OUT SCENARIO OVERVIEWS FOR OUTPUT INDICATORS BASED ON THE MAGNITUDE OF CHANGE OF THAT INDICATOR. HERE, SCENARIOS IN BLUE REPRESENT GREATEST INCREASE OF THE CORRESPONDING INDICATOR. IN THIS CASE, FILTERED SCENARIOS ARE ENTIRELY REMOVED FROM THE VIEW.

provides a view of the entire life cycle. Here, flows and processes representing sub-assemblies are shown. For gathering more detail, designers can traverse down levels and shrink the scope of the life cycle to a single manufacturing process or operation. Therefore, designers can zoom in on areas of interest in the lifecycle while retaining an overall view of the entire product.

6.2.2 Suggested design patterns

The discussed tools primarily use zooming as a navigation aid for drilling down on design data and env. indicators from overviews. We infer the following design patterns for this task.

P4: *Intent-based aggregation:* Zooming can be used as an interaction strategy for promoting transparency by facilitating drilling down on aggregated env. indicators and design-related metrics. This is particularly useful for SPD as env. indicators are often constructed by aggregating across impact categories using subjective weighting factors [54]. Aggregation also enables designers with varying levels of expertise in env. assessment to use a common visual platform for exploring the data in various levels of detail. Interested readers are directed to the paper by Elmqvist & Fekete [55] that reviews InfoVis-based guidelines for aggregation.

P5: *Multiscale design exploration:* Visual tools for SPD should potentially support multiscale exploration across both (1) system hierarchies and (2) lifecycle stages. Tools should also help designers maintain *multiscale* (across hierarchies or stages), as well as *multifocus* (across a set of selected alternatives) awareness in regards to env. performance. Such multiscale exploration tools have also been used for exploring the dynamics of env. systems [56].

6.3 Filter (T3): Filter out uninteresting items

Exploring large collections of designs presents the challenge of downselecting a set of feasible alternatives under imposed constraints. Filtering serves as an interactive technique to locate and focus on specific alternatives or regions of interest [57]. Filtering can provide dynamic visual feedback about *interesting items* through emphasis. This can be achieved by either (1) removing *uninteresting items*, or by (2) making them less prominent by changing a visual variable. Filtering can also facilitate collaborative, multi-user pruning of the exploration space.

6.3.1 Illustrative examples in SPD

shapeSIFT: The shapeSIFT interface encodes design metadata (such as material, manufacturing, and functions) using a coloring scheme (Fig. 4(a)). The underlying framework [39] provides a method for measuring similarities along multiple dimensions using known taxonomic structures for the metadata. The result of each similarity computation is a scalar measure of similarity between two parts along each dimension. This allows users to set numerical similarity thresholds (based on a reference part) and downselect parts that are retrieved by a sketch query. Parts that are *filtered out* are visually de-emphasized from the squarified layout view by graying out their background. Since the overall dimensionality of the data is preserved, shapeSIFT can facilitate *collaborative pruning* wherein, each domain expert (i.e. material, manufacturing) can individually set similarity thresholds.

QuestVis: In QuestVis, an overview visualization of the scenario space is presented to the user as a scatter plot. The magnitude of change of a particular output indicator (such as water use, and industrial energy use) is encoded using color (Fig. 4(b)). In this case, a filtering operation based on the magnitude of change in the indicator allows users to selectively remove scenarios from the viewport. To preserve context, QuestVis displays each scenario (point) in the same spatial location.

Uchil & Chakrabarti: The developed interface uses filtering for setting the system boundary of the results displayed in the env. assessment. For example, if a designer selects material extraction and manufacturing, then the LCA results update to show the impacts resulting from these stages.

i-Tree: The i-Tree emphasizes flow-specific eco-improvements when a user focuses on a particular material or energy flow. Visual filtering is achieved by retaining color on the focused items and fading the rest of the product life cycle.

6.3.2 Suggested design patterns

The discussed tools use filtering as a means for reducing the visual complexity of overview visualizations by de-emphasizing uninteresting alternatives or dimensions. Query-based interactions are also used to widening or refocusing the search space. By providing dynamic visual feedback during filtering, such tools also allow designers to explore relationships between resulting env. indicators and design parameters.
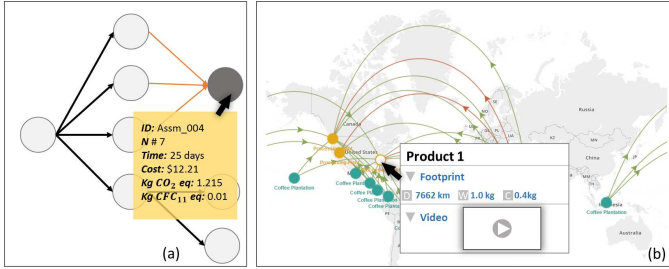
FIGURE 5: (A) VISER [40] EMPHASIZES INWARD AND OUTWARD NODE LINKS ON MOUSE HOVER. SELECTING A NODE GENERATES A TOOLTIP WITH DETAILED INFORMATION. (B) SOURCEMAP [50] DETAILS THE CARBON FOOTPRINT, AND SUPPLIER INFORMATION ON NODE SELECTION.
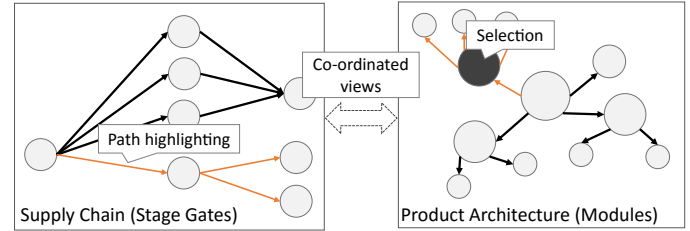
P6: *Emphasis on design similarities:* Filtering interactions should potentially emphasize similarities in design attributes. This can be useful for SPD tasks wherein designers explore similar alternatives that are more benign. Emphasis can be achieved by (1) removing items from the scene while retaining a visual variable (i.e. spatial location, color), or (2) retain items on scene and de-emphasize filtered out items by changing visual variables, e.g. color, spatial location, or size [51].

P7: *Collaborative pruning:* Visual interfaces for SPD should potentially facilitate filtering large design spaces with respect to sustainability as well as design-related metrics. Facilitating collaborative pruning of the design space among all involved stakeholders in SPD allows them to realize globally feasible outcomes, especially when information is scarce [58].

6.4 Details on demand (T4): Select an item of a group and get details when needed

When exploring a large decision space the number of data points in overviews create a high level of visual complexity. Although it is beneficial to preserve context while exploring the data, limitations in screen sizes and resolution makes it impractical to visualize details about all data points. *Details on demand* serves as an interaction technique that provides additional information about single/multiple selected objects while preserving the overview. Examples for this interaction technique include, *information tooltips* presented on mouse hover, and a separate *detail viewport* that provides information on selected objects.

6.4.1 Illustrative examples in SPD

ViSER, SourceMap: ViSER implements *details on demand* via *information tooltips*. When a user selects a node from the supply chain tree, details such as, ID label, node number, and env. impacts are displayed in a tooltip (Fig. 5(a)). Furthermore, when a user hovers over a node, the ID label is shown as a tooltip and edges directly connected to that node (both inward and outward) are emphasized using color. Similarly, SourceMap presents details about the supplier and the env. footprint of a supply stage as

FIGURE 6: VISER [40] IMPLEMENTS TWO MUTUALLY COORDINATED PANES REPRESENTING A SUPPLY CHAIN TREE AND A PRODUCT ARCHITECTURE GRAPH. SELECTING A PART FROM THE ARCHITECTURE PANE, UPDATES THE SUPPLY CHAIN TO SHOW PATHWAYS FOR THE CORRESPONDING PART.

a tooltip (Fig. 5(b)). SourceMap also presents example calculations for carbon footprint on the tooltip, promoting transparency in env. assessment.

VisEIO-LCA: A *detail window* implemented in VisEIO-LCA allows users to explore detailed information pertaining to different visualizations. For example, while exploring a visualization of the economic matrix and toxic release inventory (TRI) vector data, the detailed view presents a magnified view of a user-selected region. Similarly, when the user selects a point from the scatter plot visualization, the name of the sector and the exact value for the specific point is displayed in the *detail window*.

6.4.2 Suggested design patterns

Details on demand serves as a useful interaction technique for presenting additional data dimensions not captured in the existing visualization. These details can be presented as raw metadata or embedded visualizations. This allows presentation of details on overview visualizations while preserving the context of the overall design space. We infer the following design pattern.

P8: *Interactive detailing of hidden dimensions:* User interactions that *select* or *focus* visual elements should dynamically present details on non-visualized dimensions for multi-dimensional data such as env. indicators or design metadata. Results can be presented through mechanisms such as dynamic labels, tooltips, and visual emphasis.

6.5 Relate (T5): View relationships among items

A lifecycle of a typical product consists of multiple interacting products and lifecycle stages. This creates the need for multiple representations for lifecycle data. SPD requires designers to comprehend several such representations to fully evaluate design alternatives. Providing visual cues for relating data across these representations simplifies navigation and decision-making processes. For example, relating designs by similarity measures allows spatially representing similar designs based on a reference design. This allows designers to easily identify sub-spaces that contain designs with similar characteristics.

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6.5.1 Illustrative examples in SPD

ViSER: This interface consists of two mutually coordinated views that relate a supply chain of a product system to its physical architecture. Here, selecting a part from the product architecture graph (Fig. 6) emphasizes the corresponding pathway on the supply chain graph. This linking allows designers to relate supply chain related metrics, e.g. stage time and cost, to product-related metrics, e.g. modularity. Also, resulting env. impacts are simultaneously overlayed on both views. This allows designers to ask questions like "what is the *most impactful* supply chain stage for the *most impactful and most modular* part?"

Uchil & Chakrabarti: The interface developed by the authors used a multi-view visualization to help designers identify unforeseen relationships between design parameters and LCA results. Dynamic sliders present in the interface help designers explore the effect of a change in system boundary or functional unit on the resulting env. impact.

i-Tree: The i-Tree uses TRIZ (Theory of Inventive Problem Solving) to relate LCA results to design. To do so, the authors develop a graphical ontology that guides designers in mapping the product life cycle, identifying and emphasizing critical flows, and tracking eco-improvement. i-Tree relates eco-improvement and env. impact by visualizing criticalities— a measure of the available improvement based on the efficiency of the product or process—using a Sankey chart.

6.5.2 Suggested design patterns

Relating and visually presenting dependencies in env. indicators and lifecycle data can help designers contextualize env. assessment to design-related lifecycle variables. We infer the following design patterns based on our review.

P9: *Co-ordination of lifecycle views:* Lifecycle data should be presented using multiple mutually coordinated views. This allows designers to explore multiple representations of lifecycle data and evaluate sources of env. footprint. In these views, relations between data across the visualized lifecycle stages should be interactively emphasized. Interested readers are directed to the work by Wang et al. [59] that discusses when and how to design multiple-view systems.

P10: *Linking indicators through the lifecycle:* env. indicators should be visualized in the context of a specific lifecycle stage (such as the manufacturing or use phase) and linked to show its contribution to the overall env. footprint of the design or the system.

6.6 History (T6): Keep a history of actions to support undo, replay, and progression of refinement

SPD is an open-ended process and, most often, there is little guidance for the designer about the direction of search. Furthermore, as one of the goals in SPD is to facilitate learning, it is important for visualization-based tools in SPD to reduce the cost
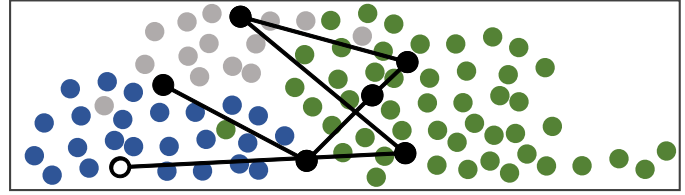

FIGURE 7: QUESTVIS [49] SHOWS HISTORY OF USER EXPLORATIONS ON THE SCENARIO OVERVIEW WITH A TRAIL. EACH CIRCLE REPRESENTS A FUTURE SCENARIO AND THE CIRCLE'S COLOR ENCODES CHANGE IN A SPECIFIC OUTPUT INDICATOR.

of exploration. This can be achieved by allowing designers to (1) visualize the consequence(s) of their decisions through the exploration process, and (2) retrace their steps and branch out in a different direction [60]. In collaborative SPD tasks, visualizing *exploration pathways* across the group can provide individual designers with an awareness of one another's decisions.

6.6.1 Illustrative examples in SPD

QuestVis: Scenario space overviews in the QuestVis interface display a trail marking recently selected scenarios (Fig. 7). This helps users create associations between input choices to the QUEST model and the output indicators for future scenarios.

6.6.2 Suggested design patterns

We found that only QuestVis allows for saving the entire history of the exploration process. While some other tools have the ability to save current state, the need to save the entire history trail is critical with the increasing complexity of the exploration process and the need for collaborative decision-making. We infer the following design patterns based on our review.

P11: *Eco-location:* Exploration paths should be visually presented to designers so that they can serve as navigation aids. Such visualizations should overlay consequences (env. indicators) due to input choices for facilitating designers' learning from previous decision scenarios.

P12: *Shareable exploration trails:* In collaborative tools exploration paths of each designer should be visualized in a shareable manner. This facilitates group-awareness of the exploration processes [61]. Saved exploration states across shared pathways should serve as anchor points for branching out neighboring regions in the design/decision space.

6.7 Extract (T7): Allow extraction of sub-collections and of the query parameters

Extraction is an interaction task that allows users to (1) create and export sub-collections containing items of interest, and (2) save and export settings, for interactions controls implemented by an InfoVis tool [19]. The overall goal is to reduce the tediousness associated with reporting or reusing previous knowledge obtained through a set of interaction procedures.
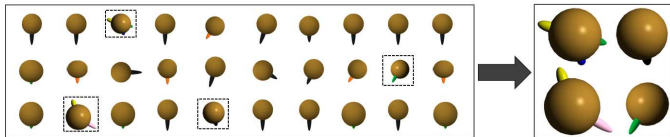
FIGURE 8: SUB-MATRIX OF OM-GLYPHS (RIGHT) EXTRACTED FROM A LARGER CO$_2$ GLYPH MATRIX OF THE ENTIRE INVENTORY (LEFT) [38]. THIS EXTRACTION STEP ENABLES USERS TO VISUALIZE GREATER DETAIL FOR A SELECTED SET OF GLYPHS. IN EACH GLYPH, THE RADIUS OF THE CENTRAL SPHERE REPRESENTS THE TOTAL SUM OF CO$_2$ EMISSIONS FOR A SPECIFIC COMPONENT IN AN ASSEMBLY. THE PROTRUSIONS FROM THE SPHERE ENCODE CONTRIBUTIONS FROM EACH LIFE CYCLE STAGE.

Providing a means for extraction is an important capability for visualization-based tools in SPD as reporting is an integral part of comparative env. assessment and design exploration.

6.7.1 Illustrative examples in SPD

OM-Glyphs: Otto et al. [38] present a matrix-style visualization of OM-glyphs that encode carbon dioxide emissions for an entire inventory of an electronic product (Fig. 8). In this view, the large number of glyphs makes it difficult for comparing glyphs with one another, and detecting data imperfections (based on the sphericity of the base sphere). To overcome such a limitation, users can extract a sub-collection of OM-glyphs in the form of a sub-matrix. As a smaller number of OM-glyphs are shown in this view, each glyph can be shown in greater detail.

QuestVis: The QuestVis interface allows users to save their value judgments (positive, neutral, and negative) for output indicators in the QUEST model. This set of values can be reloaded onto the interface for future exploration tasks.

6.7.2 Suggested design patterns

Extracting a set of alternatives from a larger design space can help designers develop *functional units* for contextualizing env. indicators to design. For example, extracting rotation-based transmission parts from a repository can allow designers to understand the env. impact of transmitting a unit torque. Furthermore, creating affordances for *extracting* and *exporting* queries, interesting results, and exploration methods can help ease the barriers to collaboration, leading to the following design pattern.

P13: *Exploration snippets:* Designers should be able to create saveable snippets of both data and metadata pertaining to the exploration process. Adoption of any designed visualization-based tools for SPD can be furthered by facilitating reuse, reporting, and exchange, of such snippets.

7 DISCUSSION & LIMITATIONS

While the set of design patterns here serve as a review of best-practices based on previous tools, the implementation of

TABLE 2: SUGGESTED DESIGN PATTERNS FOR VISUALIZATION-BASED TOOLS FOR SPD (P#) MAPPED TO TASKS IN THE TASK-BY-TYPE TAXONOMY (T#)

T1	Overview	Indicator overviews	P1
		Eco-prominence	P2
		Eco-persistence	P3
T2	Zoom	Intent-based aggregation	P4
		Multi-scale design exploration	P5
T3	Filter	Emphasis on design similarities	P6
		Collaborative pruning	P7
T4	Details on demand	Interactive detailing of hidden dimensions	P8
T5	Relate	Co-ordination of lifecycle views	P9
		Linking eco-indicators through the lifecycle	P10
T6	History	Eco-location	P11
		Shareable exploration trails	P12
T7	Extract	Exploration snippets	P13

these patterns into future tools requires design judgement. In other words, the suggested design patterns should be viewed as templates on which future tools can be modeled. We recognize that the use of our design patterns do not guarantee the success of the developed tool. Developing a checklist for creating a successful interface is prohibitively hard, not unlike the idea of creating a checklist for designing successful products. In both cases, success depends on human creativity, insight, and skill. Even so, we believe that creating a list of design patterns or templates is worthwhile as it provides practitioners with a starting point for rapid prototyping and evaluation of different implementations. This is particularly critical as the cost of creating information interfaces and evaluating them is often significantly high [62].

Furthermore, we recognize that the number of existing InfoVis tools for SPD is relatively small. Hence, our design patterns do not represent a full landscape of guidelines. In the future, we intend to re-visit our list and possibly offer a more comprehensive classification. To this end, we envision that a well-structured set of design patterns would open new research opportunities for studying both advantages and challenges in using various types of visual representations and interactions in future tools.

8 CONCLUSIONS

In this paper we have presented a set of design patterns for visualization-based tools for SPD by analyzing previous works in this domain using the task-by-type taxonomy. A summary of mappings between identified design patterns (P#) to the task-by-type taxonomy (T#) is presented in Table 2. The primary contribution of our paper is a set of design patterns useful for creating future visualization-based tools for SPD. We believe that our suggested design patterns will (1) serve as a guide for cre-

ating integrated visualization-based tools for SPD and (2) contribute towards reusable visual components to aid in quick interface wireframing. One could imagine that with community-wide agreement on design patterns such as the 13 suggested here, research groups could begin developing reusable visualization components as plug-and-play features to prototype interfaces.

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DISCLAIMER

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