Designing Knowledge-assisted Visual Analytics Systems for Organizational Environments

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ABSTRACT
We present research focused on designing knowledge-assisted visual analytics (VA) systems for workers in organizational environments. We focus on business analysts and asset managers, who work collaboratively to analyze information and make decisions. Through extensive investigations in two organizational environments, we found that these users struggle with managing and analyzing information from multiple perspectives. Their current tools lack support for aggregating, organizing, and sharing such information. To address their needs, we characterized their analytic workflows, extracted specific key knowledge actions for each task commonly found in these workflows, and designed and evaluated two visual analytics systems that support and encapsulate these knowledge actions. We provide design guidelines that should be used when designing knowledge-assisted visual analytics systems, and illustrate their effectiveness with two systems built by following them.

ACM Classification Keywords
H.5.2 User Interface: Graphical user interfaces (GUI)

General Terms
Design

INTRODUCTION
We present the design for knowledge-assisted visual analytics systems in organizational environments. Our targeted users are business analysts and asset managers, who comprise the task force that handles information analysis and decision-making for companies and government agencies. These users focus on fusing multiple streams of data, retrieving information for context-dependent tasks, analyzing and sharing their findings, and finally collaborating with others to reach decisions.

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Various systems have been developed to provide data manipulation and information analysis [12] [16]. However, as Gile et al. [8] pointed out, a major shortcoming of these systems is that they do not associate information analysis with the analytical process, and are therefore limited in providing context for decision-making. Bucher et al. [4] further suggested that information analysis is generally isolated from the user's analytical workflow, leaving a significant amount of data and information detached from an interpretation context. Therefore, it is necessary to design a system tailored to these professionals' workflows, while supporting more systematic and purposeful information analyses.

Following Zimmerman et al.'s [21] definition of design research, instead of intending to produce a commercial product, we focus on producing design considerations that support the analytical process within a knowledge-assisted visual analytics system. We consolidate the resulting design considerations into more general guidelines, which can be applied to the wide range of visual analytics applications currently being developed and deployed in today's organizational environments.

Our design study was conducted through extensive collaboration with two groups of users. From them, we learned their actual analysis needs and workflows, and with them, we concurrently designed prototype systems to iteratively identify tangible design considerations for their user class.

This work makes three primary contributions: We present a characterization of *the analytical workflow of users* and *key knowledge actions* that are required to perform individual tasks in the workflow. We describe design guidelines for visual analytics systems that facilitate the workflow through support for the above key knowledge actions. Finally, to illustrate the effectiveness of our guidelines, we introduce and evaluate two systems designed using them as a basis. (Further details on the architectures and implementations of these systems can be found in our companion papers [19] [18].)

We grounded our design based on studies with two groups of professionals in different organizational settings: bridge-asset managers in The U.S. Department of Transportation, who propose and execute strategic bridge maintenance plans; and business analysts from Xerox, who retrieve and analyze documents for information essential to the operation of the business. We closely examined these users' analytic workflows and interviewed them to learn the knowledge work required for achieving each analytical task. In general, members from both groups must utilize and analyze information from multiple channels, and are required to generate shared products effectively (e.g., a maintenance proposal or analytical report). Subsequently, they need to coordinate with multiple colleagues in different locations to agree on strategic decisions.

Specifically, through iterative prototyping with domain users, we summarized six task activities essential for these professionals' decision-making workflows. As shown in Figure 1, these six tasks are recurrent and central in jobs involving foraging and analyzing relevant information, and enable these workers to update statuses and coordinate progress with other individuals and groups. Currently, these tasks are handled dispersedly in an individual's workflow with little support for systematically aggregating, organizing, or analyzing the information.

In the following sections, we present the procedures and findings of our characterization for this domain, and its related analytical workflows. We describe the use of actionable knowledge (Section) to transform the tasks found in these workflows into tangible visual analytics design guidelines. These design guidelines include requirements that support the essential analytic tasks, as well as advanced functions. Finally, we evaluate two systems designed with these guidelines in mind.

CHARACTERIZING ORGANIZATIONAL ANALYTICS PROCESSES

To produce appropriate design guidelines for an effective knowledge-assisted visual analytics system, we closely studied our targeted users and characterized their domain-specific analytical processes. As shown in previous research [14] [5], an organizational analytical task is a process of handling multiple channels of information through the utilization of trained knowledge and current resources. Characterizing the analytical process in an organizational setting, such as a company or a governmental agency, is a complex process and requires commitment from all parties to maintain long-term collaboration.

We are very appreciative to our collaborators from USDOT and Xerox Corporation for their devotion to helping us pursue our research goals and generously providing invaluable resources. Both organizations granted us the opportunity for close, in-depth interactions with their users and to conduct surveys and interviews, which were crucial in studying their analytic processes. With the input we collected, we were able to create schematics detailing their workflows and identify the analytical tasks used in each organization.

Our design study involved two separate investigations with users from each of the two organizations. Participants varied in number, depending on the availability of these busy professionals at each time. During each investigation, data was collected using online questionnaires and/or semi-structured interviews. The data collected was used to characterize these workers' task activities within analytical processes, and further used to develop the design requirements for a knowledge-assisted visual analytics system. In the following sections, we describe the procedures and results for each investigation:

Depicting Tasks in Bridge Maintenance Process

Starting in January 2008, our university formed a research partnership with the USDOT and The North Carolina State Department of Transportation (NCDOT) to investigate novel approaches in assisting the bridge management process. One of our first actions under this research partnership was to conduct a nation-wide survey [18] regarding professional profiles, tool usage, and tool preferences. The surveys were designed to provide a baseline and statistics for comparisons between normal tools used in bridge management, and to identify potential areas for improvement.

Thirty-five out of the 50 state DOTs responded to our survey. The results clearly indicated that current bridge management systems are often insufficient in supporting effective bridge analysis. Almost all the responding states expressed the need to have a management system that would enable them to be more effective at analyzing their bridges, and that such a system needs to be customizable to assist their individual workflows.

Based on their feedback, we further conducted semi-structured interviews with bridge managers on a regular basis (every two weeks), in order to iteratively identify and propose features that can better support their analyses. Through our interviews, we learnt that bridge maintenance workflow is a process of deciding the severity, trending, relevance, and benefits of maintenance work on specific bridges, as well across as entire networks of bridges. Bridge managers hold the role of knowledge manager and are attuned to information analysis and sharing practices.

As shown in Figure 2, the first essential analytical task in the bridge analysis process is to gather all the relevant data about a particular bridge, including any known damage, previous maintenance history, and typical deterioration patterns of the materials involved. Bridge managers then analyze the obtained information, identify any need for maintenance, and write up proper maintenance plans. We also note that bridge managers often need to develop their own custom analysis routines. Depending on available resources, a bridge man-

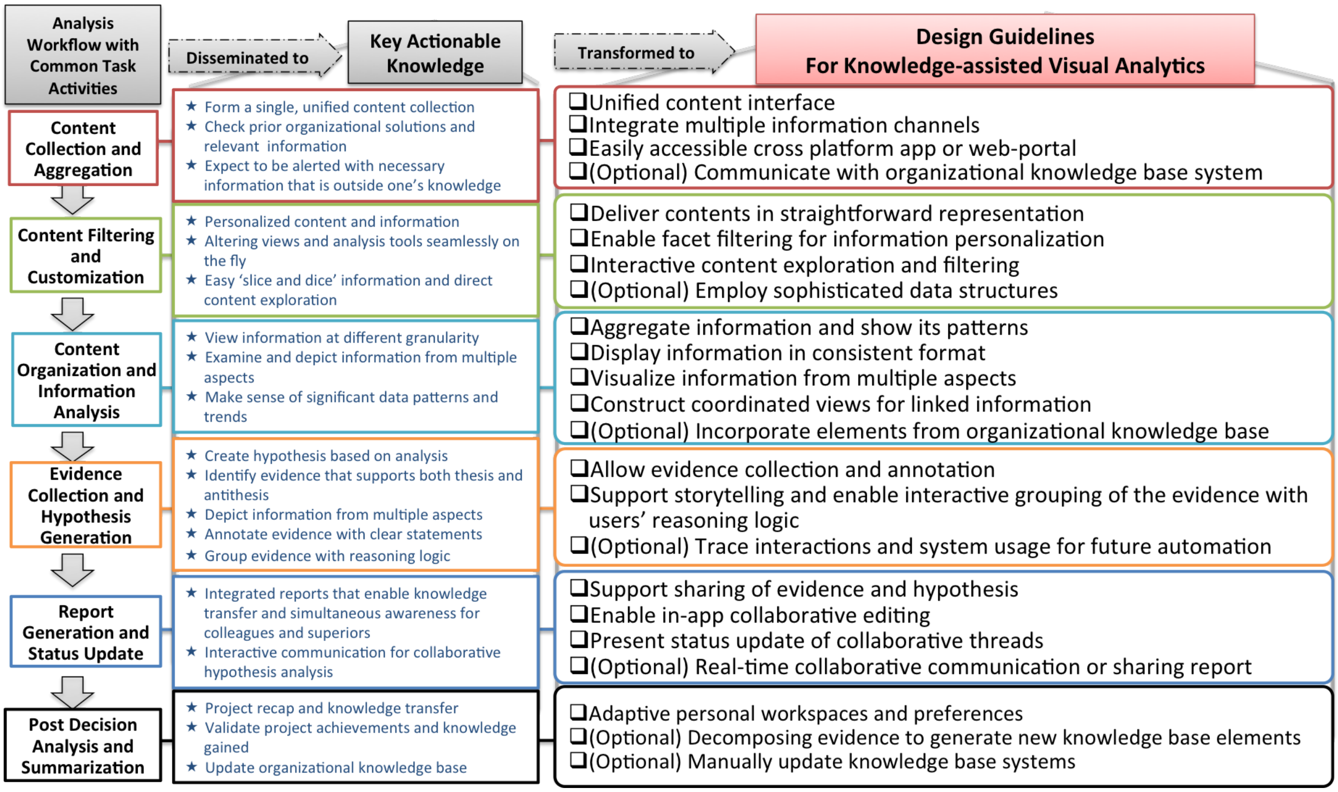

Figure 1. An overview for our design guidelines. An organizational workflow is characterized into six common task activities. Each activity is disseminated into fine-grained actionable knowledge. VA design guidelines are consolidated by transforming this actionable knowledge into practical functions. Note: Given the different degree of completeness, only a subset of the listed actionable knowledge is typically used in accomplishing each task.

ager's strategy can be very different from their peers', requiring a different combination of the above analysis processes. In addition, sometimes even a single manager needs to utilize multiple alternative analytical approaches due to changes in priorities. At the heart of these individual routines are different combinations and sequences of the above analytical processes. Therefore, it is important for a system to provide bridge managers with the flexibility to combine and sequence these analytical processes to fit their own, customized workflows.

Understanding Business Information Analysis

We further carried our momentum and analysis methodologies into our project with Xerox Corporation in the summer of 2009. In an organizational environment, such as Xerox, employees' document-centric activities result in the creation of many diverse information streams, including email threads, calendar entries, web browsing histories, and versions of office documents. Many of these documents contain information essential to the operation of the business, such as project proposals and emails capturing product discussions. Thus, our goal in this project is to investigate and design a system that is effective to assist corporate employees in both managing these information streams, and extracting desired business information from them.

To understand this particular information analysis process, we conducted 30 semi-structured interviews with Xerox employees. The interviewees held a broad range of positions, including product researchers who needed to write proposals and research papers, managers who were in charge of business planning and marketing, and administrative staff members who oversee hiring. These interviews were designed to provide us with baseline statistics about the general information analysis methods that were being used in managing business information.

The results of our interviews showed that the most challenging problems for the corporate employees was handling large amounts of content and, more importantly, managing information from multiple channels simultaneously.

As shown in Figure 2, the analytical tasks of finding business information often include content aggregation, information organization and correlation, and sharing and collaboration. To analyze certain business information, an employee often starts with aggregating content, such as possibly relevant documents, into a single location. They will then filter this large collection of data, and attempt to organize it in a clear and consistent manner to support the awareness and sensemaking process. We noticed that sharing their analysis findings and providing status updates are crucial activities in these employees' workflows. Because most current tools lack support for these critical functions, employees will often resort to paper formats or email to communicate with other colleagues about the business information which they have found or their need for help finding it.

Identifying Six Common Task Activities in Organizational Analytics Processes

To further characterize the common task activities found within an organizational environment, we consult the Think Loop model [15], grounding the usage of visual analytics in a theory of information flows through the users' analysis processes. We found that, while different organizations shared diverse tasks, each's analytical processes constituted a series of similar, loosely defined, and collaborative task activities. Users accomplished analytical goals via subtasks, had focused targets, and accessed a range of services and resources [7]. As shown in Figure 2, we identified six task activities common to organizational analysis processes:

- *Content Gathering and Aggregation:* users identify appropriately-scoped content to form basic analytical contributions. They seek and extract information from multiple channels relevant to the analytical tasks.
- *Content Filtering and Customization:* users use filtering to familiarize themselves with content they have collected. They also personalize the analysis environment in which this content is filtered.
- *Content Organization and Information Analysis:* users organize the collected content and examine it from multiple perspectives to look for data patterns and desired information.
- *Evidence Collection and Hypothesis Generation:* users create hypotheses regarding their analyses, and collect related supporting evidence.
- *Report Generation and Status Update:* users increase visibility to others regarding analysis status, by providing notification and updates on the progress of their analyses,
- *Post-Analysis and Summarization:* users focus on validating project achievements and introspecting workflows, after accomplishing an analytics process.

TRANSFORMING ORGANIZATIONAL ANALYSIS PROCESS INTO VISUAL ANALYTICS DESIGN

Designing a knowledge-assisted visual analytics system requires supporting the analytical workflows of the users. While the aforementioned task activities are useful in describing a general analytic process, they are often too general to provide any specific guidelines in actual system designs. Therefore, the first step in our design research was to search for tangible artifacts that could help breakdown these high-level semantic tasks. These target artifacts must meet two basic requirements: (1) they need to be concrete enough for practical visual analytics system designs, and more importantly (2) they must be consumable for the users, who need to decide how to make use of them, without introducing a considerable cognitive overhead.

In Search of Tangible Design Artifacts

Many approaches have been used to denote such artifacts. We examined previous research in the intelligence analysis and knowledge management communities, and focused on understanding the use of the knowledge process (e.g. knowledge creation, consumption, and transfer) within the analytical process. Similar to Heuer's [10] perspective on knowledge as a dynamic expectation of information, we emphasize the importance of knowledge actions to support the transitions between different analytical task stages, and further integration within the analytical process as a whole. In addition, Nonaka et al. [11] also explored the general knowledge conversion processes that can guide design of organizational decision support systems. Again, these knowledge processes are too high-level to be useful in directing a specific design for a visual analytic system.

Enlightened by the Theory of Action [2], we followed Anrigyri et al.'s definition, and described our target artifacts as a series of ***Actionable Knowledge***. Actionable knowledge is explicit symbolic knowledge,typically presented in the form of *tradeoffs for action* or *rules* [13], which allows the decision maker to recognize some important relations and perform an action, such as targeting a direct marketing campaign, or planning infrastructure maintenance aimed at reparing those assets with lowest health. The nature of actionable knowledge fits well with our two requirements in that: (1) it represents the fine-grained elements of each analytical task, and thus is quite instructive for the design of a knowledge assisted visual analytics system; (2) it is extracted from domain users' knowledge actions, and therefore can be consumed without additional cognitive overhead.

Representing Organizational Analytics Processes using Actionable Knowledge

As illustrated in [2] [4] [6], there are many approaches to model actionable knowledge. Given our advantage of a close working relationship with actual domain users, we adopted the domain-driven modeling process, and grounded our search for actionable knowledge on the interviews and surveys with our two interviewee groups.

During the interviews, we asked the participants to envision the hypothetical process of carrying out their usual tasks with their regular tools and working environments. We encouraged them to also think about additional functions that might be useful but not yet available in any of the tools they typically used. Specifically, we asked our participants about the fine-grained knowledge actions they used in their daily practices, the

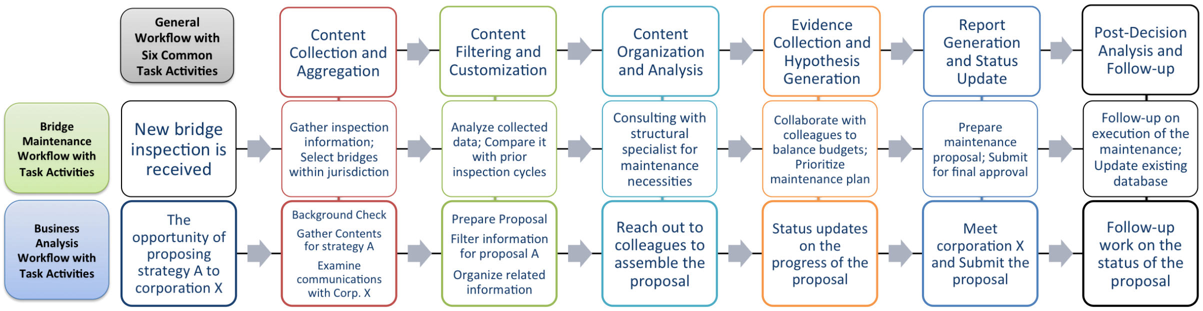

Figure 2. This chart describes the workflow in each organizational environment. (Top) The six task activities common to both organizational analysis processes. (Middle) A typical analytical workflow for bridge maintenance planning. (Bottom) A typical analytical workflow for a business information analyst.

essential tools they have, and how they utilized these tools to execute each action. In doing so, we were able to identify key actionable knowledge that a tool should support to improve productivity and reduce workload.

In their responses, our interviewees expressed the importance of actionable knowledge to the organizational decision making process. In their analytical process, actionable knowledge is followed to respond to different situations, and illuminates potential action paths for overcoming obstacles. The use of actionable knowledge further directs these professionals to discover certain information or data patterns, and helps them to react to the advantages of a specific task. For example, for the content aggregation task, a bridge manager often needs to check multiple sources of information (e.g. structural, financial, and historical) prior to their response for a new bridge maintenance request. During this process, actionable knowledge regarding where to look for information, and how to examine the information, plays a significant role in addressing this task.

Tools, in this context, are considered as means to transform the knowledge into desired task actions. Users primarily use tools such as email/documents/local folders, to produce and communicate task related contents and information. In the process, their domain knowledge (i.e. the expertise) is employed, and further results in context-dependent actions that are used in their analytical process. These professionals currently posses and use a number of different tools; however, we found that both groups were severely lacking tools that were actually designed to support to their analysis workflows. This finding pointed to the need for a tool that encapsulates the users' actionable knowledge and helps them effectively perform necessary actions.

Based on the feedback from our interviews, we summarized a set of selected actionable knowledge that describes the six common organizational task activities. As shown in Figure 1, every task in an analytical process is decomposed into a set of fine-grained actionable knowledge. Note that, this list contains only a subset of all the collected actionable knowledge; some of the stated actionable knowledge is unclear, ambiguous, or contradictory, and is therefore excluded from this list. Also as seen in Figure 1, we have constructed a clear mapping between high-level tasks and their fine-grained tangible artifacts. This mapping provides clear insights into the organizational workflow. More importantly, it is further transformed into a range of important design requirements for creating an effective knowledge-assisted visual analytics system.

Transforming Actionable Knowledge into VA Design Guidelines though Prototyping

Our next step was transforming this list of specified actionable knowledge and requirements into proper visual analytics designs. We followed the design theory for enterprise-knowledge-processes [13], and conducted several iterations of prototyping in close collaboration with our users to encapsulate their actionable knowledge into functions. Although both groups shared similar common analytical tasks, our prototyping methods with them were quite different (considering their diverse workspaces and time constrains). Specifically, we used a more frequent, throwaway prototyping [1] method for our collaboration with Xerox. Given the shorter design cycle (three months), the throwaway prototyping guaranteed us more design iterations and, more importantly, allowed us to explore broader options for transforming the actionable knowledge into visual analytics designs. A sample of the intermediate prototypes can be seen in our companion media.

Based on our iterative prototyping with business analysts, we found a clear preference for a unified, intuitive, and less intrusive system that can help effectively retrieve and manage desired information. Therefore, we finalized our prototype and implemented Taste [19]; an interactive visual analytics system that enhances employees' capabilities to search and share business information. As shown in Figure 3, Taste is structured to embed information retrieval cues into a coordinated multi-level visualization system. At a high level, Taste encodes these cues with a set of three visualizations, a Facet view (A), a Temporal view(B), and a Entity Tag view (C). Each view presents a particular aspect of

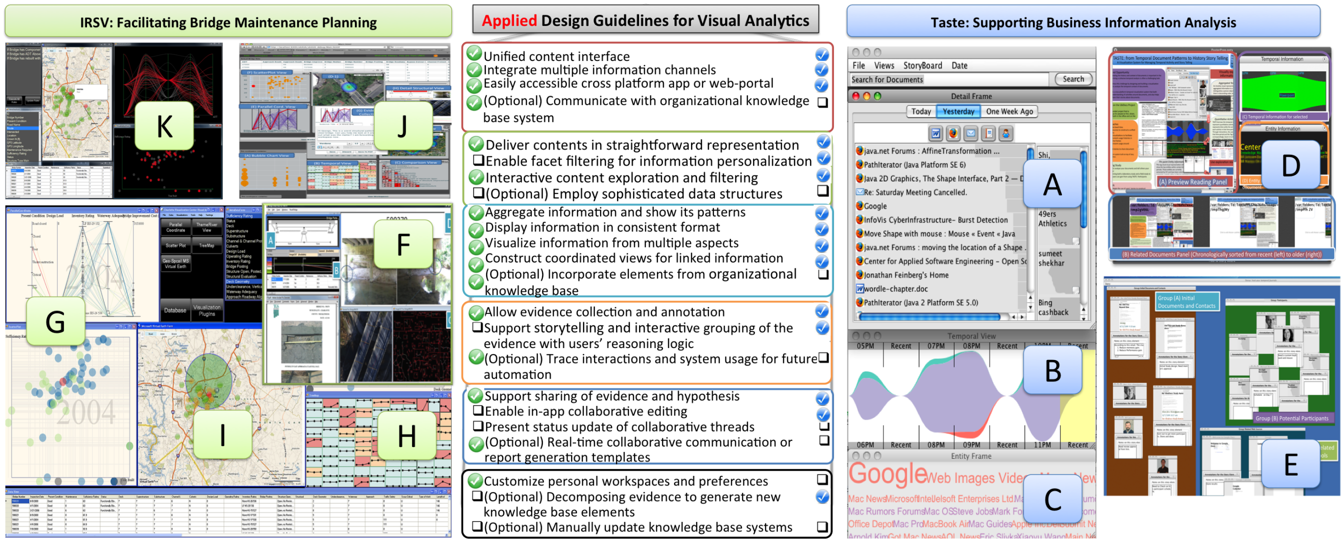

Figure 3. An overview for both the Taste and IRSV systems. (Middle) The design guidelines actually incorporated within each system are indicated by marked checkboxes. (Right) Taste consists of (A) Facet view, (B) Temporal view, (C) Entity Tag view, (D) Detail view, and (E) Storytelling view. (Left) IRSV contains multiple analysis views, including (F) Detailed structural view, (G) High-level structural view, (I) Geospatial view, and (H) Temporal analysis view. In addition, IRSV provides two variations: (K) a knowledge base integrated system and (J) a web-based system.

document activity information across entire collections. In lower-level views, Taste presents visualizations that integrate related activity information for single documents(D). Using this multi-level structure, Taste helps users to cohesively depict document activity from different points of view, and effectively find the desired information.

Thanks to a long-term collaboration plan, we were able to conduct a longer-cycle, more functionality-based prototyping process with the bridge managers at both US-DOT and NCDOT. This iterative functional prototyping [9] simulates application behavior and helps to ensure that more of our design system is understood at each step of the collaboration. In each iteration, we invited the bridge managers to test and evaluate our prototypes by working with the system to perform actual bridge analysis. Based on their suggestions and requests, we then refined, re-designed, and re-implemented the prototype system to increase its effectiveness to support the bridge analysis process.

During a nine-month period, we generated over ten functional prototypes, including various changes to the visualization and interface designs. Over the course of past two years, our prototyping has resulted in a final set of variations of the system. These all focus on providing support for bridge management using integrated remote sensing and visualization, so we generally refer them as IRSV. While each of the systems is designed to accommodate requirements for different use cases, all follow a similar set of underlining actionable knowledge, and were designed to achieve the same goal: to provide examination of heterogeneous data sources and facilitate effective bridge maintenance planning.

At the heart of IRSV, we designed a set of visualizations to help bridge managers organize and analyze their assets from the multiple perspectives essential to their decisionmaking process. As seen in Figure 3, these visualizations were designed to perform the three high-level analyses: structural analysis (G), temporal analysis (H), and geospatial analysis (I). For lower-level tasks, we designed a structural detail view (F) to automatically link information between each bridge component, and provided bridge managers with an intuitive visualization to interactively analyze specific corresponding information. All of these visualizations are tightly coordinated together in such a way that an action performed in one view affects all other views. Implementation details can be seen in our companion papers [18] [20] [17].

EXAMPLES FOR SYSTEM DESIGN AND EVALUATION

Both Taste and IRSV were designed following our guidelines. These knowledge-assisted visual analytics systems are implemented to support the analytic processes encountered in organizational environments. Through iterative prototyping processes, each was tailored to the analytical workflow of its target domain. As shown in Figure 3 (Middle), the design guidelines actually incorporated within each system are illustrated separately by marked checkboxes. We also conducted user-studies to evaluate the utility of these systems.

Instead of emphasizing technique details, our discussion below focuses on evaluations for the effectiveness of our systems to support domain analysis processes. Specifically, we summarize the users' feedback and comments, and use these to assess the performance of our systems in facilitating the common task activities. We have also planned future improvements for the systems based on the users' suggestions.

Taste: Supporting Business Information Analysis

To evaluate Taste, 21 Xerox employees participated in both lab and field studies using the tool. In the following subsections, we describe how Taste was found to be useful and effective in facilitating each of the six common task activities in the domain analysis process. Detailed statistical results for this evaluation can be found in our previous report [19].

Gathering content into a unified visual interface

At the heart of Taste is a transparent, real-time, contextual data capturer, which was designed to capture the user's activities around office documents, calendars, emails, etc. Taste creates an index of documents on a user's machine, and logs information about the user's activities with these documents. Taste stores this information, along with copies of the documents, in a unified repository. All captured information is then indexed and grouped with its related documents, and is interactively presented to the user through Taste's visualization interface, as shown in Figure 3 (Right).

All participants indicated the usefulness of this unified interface. They agreed that integrating multiple information streams into a single interface sufficiently encapsulates their actionable knowledge, reducing search times for related information. They believe this could greatly assist them in gathering and aggregating contents from multi-channels

Enable facet search for content filtering

As shown in Figure 3 (A), Taste utilizes the Facet view to aggregate both the documents and the people with whom a user has previously interacted. This visualization allows the users to filter and sort information based on automatically extracted data facets, including type (person or document) and format (email, text document, etc.). Facet view further sorts and displays document activity by importance, which is measured by frequency and users' dwell time.

When presented to the participants, they spontaneously formulated a variety of facet filters to find information. They were generally satisfied with the efficiency of using Taste to 'slice and dice' information, and appreciated the flexibility to perform customized analysis.

A common suggestion was to be able to also create formulas to sort the documents with customized measures. One analyst indicated that introducing customized time factors (such as increasing the importance of a more recently created documents over older documents) would be especially useful for filtering.

Interactive Information Analysis

Besides the facet view, Taste also supports high-level content analysis based on both temporal information and content keywords (See Figure 3 (B) and (C)). Taste utilizes the temporal view to show how a user's activities unfold over time, and presents the temporal trends and patterns of a user's document activities. This view allows the user to interactively drill down to a specific time, and helps the users examine the content, which occurred in that time span. In addition, an entity tag view is used to enable fast entity browsing. This is implemented using an automated entity extractor, which extracts entities, such as company name, contacts, etc., from all of previous documents. As shown in Figure 3 (C), Taste enables users to focus on a specific entity, and examine any information related to it.

In the low-level view, Taste incorporates a detail view (Figure 3 (D)) for depicting a single document from multiple perspectives, such as its related temporal information and other versions of the document. All views in Taste are coordinated, such that updates in one view are immediately reflected in the others.

In our studies, Tastes was compared with other existing tools to assess its analysis capabilities. The participants were generally positive about Taste's effectiveness for retrieving and analyzing business information. All participants agreed that the ability of viewing information from different granularities can largely help them filer and analyze information.

One suggestion was to provide finer-grained categories, and display more information for entities. One participant suggested that the current categorization is too broad by referencing a common expectation: Instead of general, high-level categories like browsing, email, etc, usually the categories of interest are more narrow like "email with Bob" or "browsing about JAVA")

Using Storytelling to generate and share reports

By utilizing an interactive storytelling view, shown in Figure 3 (D), Taste allows users to interactively collect evidence, annotate it, and share it with others. The storytelling view allows the user to take a more active role in information tracking, and enables them to express the information relationship based on their own knowledge. Whenever a user comes across an interesting information object in Taste, they can directly add that object to a new or existing story view. Once an element is in a storytelling view, the user can further annotate or tag it, and can group different story elements based on their reasoning logic.

The story created by one user around a collection of people and documents may be of interest to other users as well, so Taste allows stories created in one instance of the system to be shared with users in another instance. Analysts who receive these shared stories, are able to modify them based on their understanding of the topics, and add or suggest removal of story elements. By sharing their stories about document activities, groups of employees can now understand those activities better, and improve information analysis for all members of the group.

While the story feature is new, many participants found the idea of collaboratively searching for information intuitive, and felt that the feature was practical and useful. Although we didn't set up a collaborative environment for participants (due to privacy concerns), participants were still interested in utilizing the story view and tried to share findings between different instances of Taste.

In summary, while Taste has so far only been evaluated by a limited number of participants (albeit actual target users), it appears to be a promising technology and a successful design. Based on the feedback we have received, we believe the design of this visualization successfully encapsulates the actionable knowledge and supports the analytical workflows that are essential for business information analysis. Through our on-going collaboration, we are further refining its basic functions and enriching it with more advanced features.

IRSV: Facilitating Bridge Maintenance Planning

Our evaluations of IRSV and its variations were performed iteratively throughout the collaboration, and were mainly conducted with a group of bridge managers from both North Carolina DOT and Charlotte DOT (CDOT). These 12 (10 male, 2 female) bridge managers participated in at least three sessions of onsite evaluations

In the following subsections, we summarize feedback from these evaluations and assess the systems (multiple IRSV variations collectively) for their effectiveness in facilitating each task activity encountered in bridge maintenance planning.

Integrating heterogeneous data into one interface

As shown in Figure 3, IRSV provides bridge managers with a unified content interface that combines multiple streams of bridge information. It can incorporate a range of data sources, including National Bridge Inspection Standards (NBIS) datasets, high-resolution aerial images, and Light Detection and Ranging (LIDAR) scans. In addition, IRSV provides an advanced feature, incorporating knowledge contents from an ontological knowledge structure. As detailed in our previous report [20], using a service-oriented-architecture, IRSV has been extended to communicate with the knowledge base, access and fetch the inference results, and present them in a cohesive visual interface.

Through comparisons to existing bridge management systems, it was clear that IRSV was appreciated for its efficiency in contents aggregation. All participants considered the visual interface well addressed their information retrieval needs, representing cohesive and useful for bridge information. Moreover, they were excited about the ability to access and follow prior practices and guidelines that were embodied in the knowledge base.

Customizing analysis workflows

Because it was built with a modular architecture, IRSV allows bridge managers to extend the system to incorporate advanced visualizations and more effective data models. Each visualization component integrated within IRSV was designed to be interchangeable with other equivalent visualizations. Furthermore, IRSV provides bridge managers with the flexibility to combine and sequence different visualizations to fit their individual analysis routines.

All participants appreciated the flexibility of the interface, finding it useful for customizing the system to only utilize the necessary visualizations in their particular practices. They spontaneously formed a variety of visualization combinations in order to find bridge assets. The most common strategy used was to combine a geospatial window with scatter plot view to gain information for the most recent changes of a particular bridge. A manager from NCDOT further pointed out that,"[IRSV] will greatly shorten the catch-up time between my learning to use the system and my actual use of it."

Analyzing information from multiple aspects

All participants noted that IRSV provided a visual exploration environment to help them analyze information from multiple aspects. The capability to perform not only geo-temporal analysis, but also structural analysis was of great value to their decision-making process (See Figure 3 (G)(I)(H)). One of the managers commented that, "[the] linked visualizations provide me with a cohesive understanding about the data that I am working on. It reduces the time I spent on manually searching for information, and helps me focus more on the task itself."

In particular, seven out of the 12 bridges managers pointed out that the temporal analysis in IRSV provided them with the capability to effectively monitor changes in bridge conditions and identify maintenance candidates. In addition, after familiarizing themselves with the concepts and usage of the visualizations, most bridge managers (9 out of 12) noted that the capability to examine bridge structures simultaneously from multiple levels (overview and detailed view) allowed for effective transitions from examining large amounts of data to inspecting bridges one at a time.

Evidence collection and report generation

As shown in Figure 3(J), IRSV also supports interactively collecting, annotating, and sharing analysis findings between different collaborators. Using a web interface, IRSV treats individual visualizations and group workspaces as collectable items. It enables bridge managers to directly drag and drop these items into a sandbox, designed to collect all the findings and sort them temporally. IRSV further allows bridge managers to use the collected evidence to support their analysis hypotheses and create analysis reports. The bridge managers can directly combine findings that can support their reasoning and share them with colleagues, through built-in sharing channels or emails.

Most participants found the idea of collaboratively managing bridge information intriguing. They consider our approach practical and useful for creating preliminary analysis reports. There was significant interest in utilizing the features that allowed evidence to be reported and shared with others. While we are still refining these features, we have seen great potential for IRSV to support the inherently collaborative nature of bridge maintenance planning.

In summary, IRSV was designed by following our design guidelines set forth earlier in this paper. It has been deployed to USDOT for daily use and testing. Based on feedback from bridge mangers, IRSV appears to be a successful design and a useful visual analytics system that effectively supports the bridge maintenance management process. The effort to enrich IRSV is still on-going; we are working closely with bridge mangers to identify new actionable knowledge that requires advanced features, including web-based collaboration and post-analysis.

LIMITATIONS

We undertook this research to better understand the pragmatic analytical processes in an organizational environment, and identify practical design guidelines for visual analytics systems. To this end, we consolidated our design guidelines into characteristics for the six common analytical task activities, their related actionable knowledge, and interactions between the two. We found that actionable knowledge plays a unique role in addressing important problems in organizations, and affects users' performance. Therefore, we transformed this knowledge into design guidelines for visual analytics systems. We hope that our guidelines will help others provide better support for domain analytical processes within their visual analytical applications.

There are limitations to our research which must should be addressed. Generalizability of our design guidelines is limited because this research was conducted within only two organizations. We attempted to mitigate local biases by increasing the number of participants. Nevertheless, different training backgrounds, personal preferences, and project time constraints could engender different analytical conditions.

Moreover, our research characterizes the domain analytical workflow through interviews and surveys, which generally are self-reported by participants. Our research was also limited, in that it modeled the analytical workflow from a retrospective perspective, whereas Brows et al. demonstrated that problem spaces and solutions are established and change dynamically in interactions with people and the environment [3]. Therefore, our understanding of domain analysis and actionable knowledge is constrained to the users' general way of performing tasks.

Finally, our research is limited by its evaluations with domain experts. We evaluated Taste with formal studies and IRSV with informal case studies. Developing evaluations, strategies, and methodologies to accurately assess the effectiveness of a knowledge-assisted visual analytics system is challenging. At this point we do not have a clear outline on the best evaluation approach; the design of guidelines for evaluating a knowledge-assisted visual analytic system would be one interesting future direction for our research.

However, while we recognize these limitations in our work, we believe supporting organizational analysis processes is important visual analytics research. Our design guidelines (Figure 4) illuminate the role that a knowledge-assisted VA plays in such complex problem-solving environments.

CONCLUSIONS

This paper has presented two years of iterative design efforts to explore and advance the design of knowledge-assisted visual analytics systems. Based on our extensive interactions with domain users, we identified and consolidated six common task activities that are generally used to perform organizational analysis. To decompose these high-level tasks to implementable artifacts, we further reframed the problem and disseminated these tasks into actionable knowledge that illustrates the fine-grained functional requirements for each task. Using these requirements, we designed and implemented two knowledge-assisted visual analytics systems for our collaborators.

Our primary contribution is the resulting set of design guidelines that, when implemented, allow visual analytics researchers to effectively collaborate with domain users, and to empower users in organizational environments to effectively accelerate their analytical processes. These guidelines provide design considerations for both high-level task activities and low-level functional requirements. In addition, we have summarized a set of evaluations that show the effectiveness of visual analytics systems designed using our guidelines as a basis.

We hope that by proposing these general guidelines, we can begin a serious discussion of design considerations critical for producing effective knowledge-assisted visual analytics systems. We will continue to evaluate and refine our guidelines with current and future collaborators. In addition, we hope that these guidelines will lead to potential impacts in today's organizational environments.

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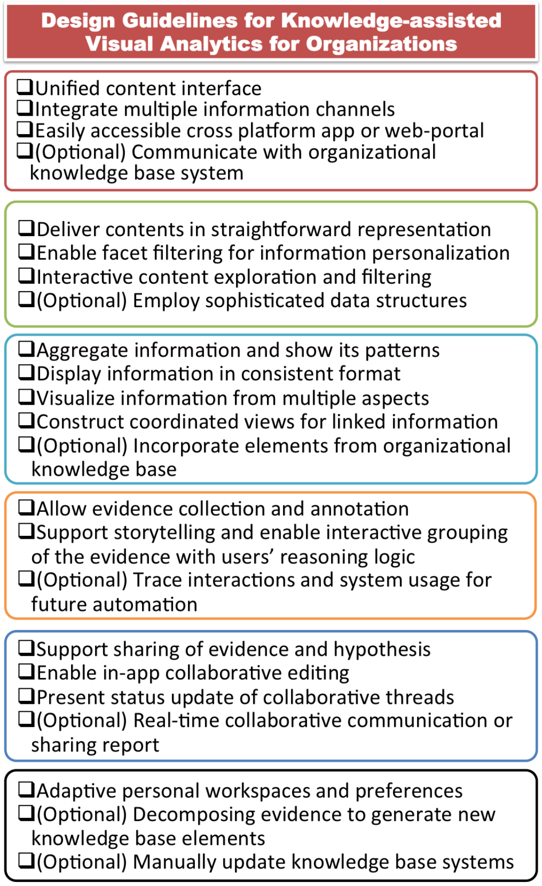

Figure 4. Our design guidelines in checklist form.

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