Towards an Adaptive Visualization System in Context-Aware Environments

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Abstract. To provide good visibility of present and potential future contexts and improve system usability and effectiveness, context-aware systems need support for developing effective visualizations of both context and user problem data. However, it is quite difficult to maintain visualization effectiveness across different problem domains, stakeholders, purposes and/or time. Although many existing visualization techniques can provide reasonable support for developing visualizations effective under a certain context, they are still weak for maintaining visualization effectiveness under varying contexts. To address these problems and requirements, this paper discusses contextual factors that may affect visualization effectiveness and proposes a context adaptive visualization framework to guide the development of visualization systems that can be embedded in or used together with context-aware systems in order to develop and maintain effective visualizations. Furthermore, it demonstrates an implementation of the proposed framework through a sequence of context-driven visualizations.

Keywords: Context adaptive visualizations · Context-aware systems · Visualization context · Context adaptability · Framework · Implementation

1 Introduction

Context-aware systems refer to information systems that can sense problem and user contexts of use, detect contextual changes and proactively respond to the changes by adapting system operations and services at runtime [1, 2]. They are often applied to deliver useful relevant information and services to the right users in the right time at the right place. Typical applications of context-aware systems are mobile systems, tour guide, and smart homes, hospitals and class rooms [3]. An essential goal of context-aware systems is to improve usability and effectiveness by explicitly taking the context of use into account [3, 4]. This requires system designers and developers to obtain a thorough understanding of possible contextual situations, reasoning rules and system adaptation alternatives at design and compile time, and also requires context-aware systems to be capable of inferring user intent based on the context input as well as selecting appropriate system operations to execute at runtime [1, 3, 4]. In addition, it is important that context-aware systems support functionalities such as informing users of

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the present contextual situations, providing feedback/confirmation to users, enforcing user identity and action disclosure and allowing users to control system behaviors [1].

The above goal and requirements highlight the need of having effective visualization systems embedded in and/or designed separately to support context-aware systems in order to visualize the present contextual situations, future context alternatives inferred from the context of use and data of the decisional problem(s) to be addressed. To support this, a common practice is to apply appropriate visualization techniques to visually encode and present the context and problem data and enable users to interact with the data. Reviews on representative visualization techniques and applications can be found in [6–8]. Although many existing visualization techniques and applications can provide reasonable support for developing visualizations that are effective under a certain context, they are still weak for maintaining visualization effectiveness when the underlying context changes. The same visualization may attract stakeholders with different background knowledge, cognitive characteristics and visual preferences, and can be applied to address different decisional problems for fulfilling different purposes. However, Visualizations effective for one problem domain/stakeholder/purpose and/or time may be ineffective or even inapplicable for others. For example, a beginner-level user may prefer visualizations dealing with smaller chunks of data at one time and require step-by-step support for how to manipulate visualizations, while an expert-level user may be interested in more sophisticated visualizations presenting larger volumes of data and need support for advanced information analysis and pattern discovery.

To address the above problems and issues, context-aware systems need include visualization subsystems or be used together with separate visualization systems that can offer flexible support for creating/manipulating/transforming/improving/disposing visualization solutions. The visualization systems also need to explicitly consider the impact from the relevant contexts. To address these requirements, we propose a context adaptive visualization (CAV) framework, which employs a mechanism of designing and developing visualizations through integrating and manipulating appropriate context-related and visualization-related data, models, solvers and scenarios and maintains visualization effectiveness by adjusting these building blocks.

The goal of this paper is to provide guidance on designing and implementing visualization systems for context-aware environments. In this paper, we explore principal contextual factors affecting visualization effectiveness in Sect. 2. Then, in Sect. 3, we proceed to discuss the CAV framework and how context profiles and visualization scenarios can cooperate with each other to develop effective context adaptive visualization solutions. To validate the CAV framework, we implemented a prototypical system, and in Sect. 4 we provide a context-driven description of the system to demonstrate its support for maintaining visualization effectiveness.

2 Contextual Factors Affecting Visualization Effectiveness

Context is a broad term and can be articulated in many different ways depending on the underlying research domains. For example, from the perspective of human-computer interaction, context is considered as any situational information that characterizes a user, system application and user-system interaction [2]. In the area of mobile computing, context is treated as knowledge determining the status of users or IT devices such as surroundings, situation, task and location [9]. In the domain of context-aware systems, Vrbaski et al. [4] consider context as any contextual information associated with the computing, user and physical environments.

With a specific focus on information visualization, we define visualization context as the information of any environmental entities that can influence visualization design, implementation, application and evaluation. Visualization context is concerned with three essential aspects, that is, the decision problem(s) of interest, the stakeholders and the visualization purposes that they intend to accomplish. These aspects may involve contextual information about relevant problem situations, time, space, social context, and technological context (including hardware and software). They can also encompass the information regarding the visualization profiles of stakeholders such as their cognitive styles, personal characteristics and preferences, pre-knowledge, age, gender and even their mood when making decisions. The effectiveness of a visualization depends upon the context where it is applied. It is the visualization context that determines what visual designs are most effective for aiding visualization stakeholders to address their decisional problems of interest and to fulfill their intended purposes. The design elements (e.g. border, background, joint of elements, etc.) involved in a visual design can have significant influences on its stakeholders' understanding and interpretation of the underlying data [10].

By reviewing and synthesizing the existing context classifications and visualization contextual information (e.g. [11–14]), we propose a visualization context model (Fig. 1) to highlight four principal visualization dimensions, that is, problem, stakeholder, purpose, and time. Each dimension consists of a series of contextual factors. More specifically, the problem dimension is concerned with the contextual information in regard to the problem situation to be supported and potential solutions.

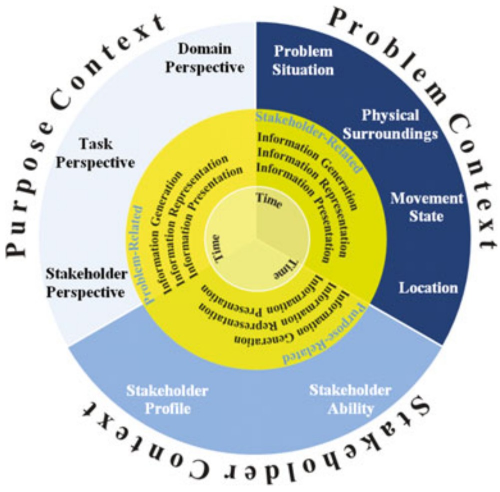

Fig. 1. Visualization context model

The stakeholder dimension involves any stakeholder-related aspects that can affect the design, development, cognition, interpretation and/or evaluation of a visualization by different kinds of stakeholders. The purpose dimension incorporates the contextual information about what a visualization stakeholder is trying to achieve through applying the visualization in a particular domain to address/accomplish a certain problem/task respectively. The time dimension concerns the time data (such as year, season, month, week, day, time, etc.) associated with decisional problems, stakeholders and purposes.

Based on understanding of visualization context, we introduce the CAV framework to help with handling context complexities in the following section.

3 Context Adaptive Visualization Framework

To support developing and maintaining effective visualizations under changing contexts, we propose a three-tier context adaptive visualization framework (Fig. 2). This framework is a conceptual level sense and respond model demonstrating the key building blocks of a context adaptive visualization system, and reveals the mechanisms of how these building blocks could relate together for creating and managing context adaptive visualizations. It leverages context profiles and visualization scenarios to aid in (1) the sensing of contextual changes (2) the analysis, transformation

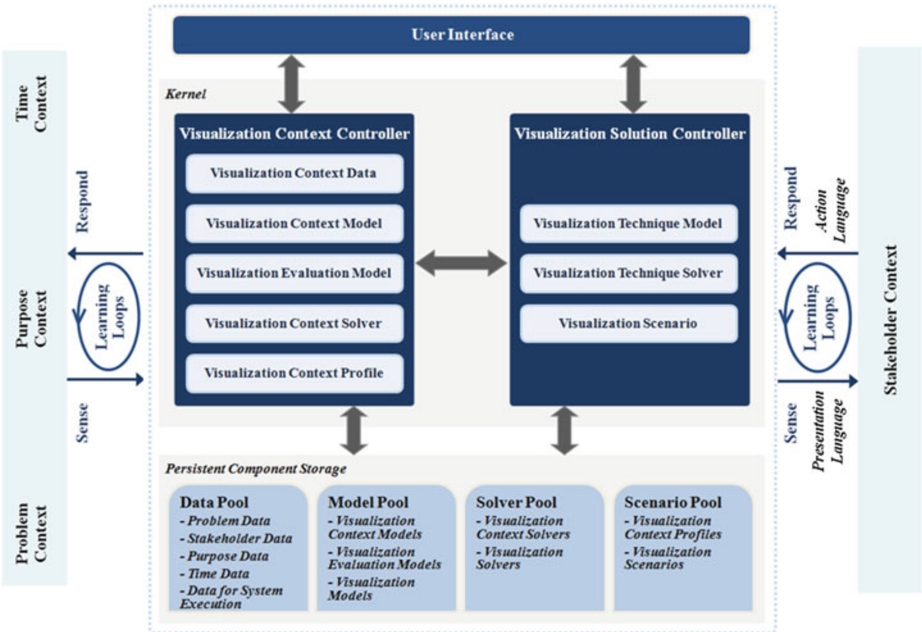

Fig. 2. Visualization context model

and learning of the new contexts and (3) responding to the contextual changes and the associated visualization requirement changes.

As illustrated in Fig. 2, this framework supports sensing the problem/stakeholder/purpose/time contexts and responds to it through the creation and adaptation of visualization. We envisage it as a two-stage process. In the initial stage, the visualization context/real world is sensed through various mechanisms such as real time feeds from context-aware systems, databases, and human input which together contribute to CAV understanding the problem, purpose, surrounding, state, time, tasks, etc. This understanding by CAV and subsequently by users enables them together to respond to what has been sensed through a variety of measures. The responses could be at different levels: parametric change (single loop learning), introduction/modification/deletion of variables of model (double loop learning), and/or transformational changes at a deep and broad level (triple loop learning). Triple loop learning is especially important when the context changes significantly. Furthermore, CAV mediates between visualization problems and users through the explicit provision of action and presentation languages. Users may engage with CAV through a proper visual presentation language which enables them in understanding and sensing the contexts and responding appropriately through a visual action language. Obviously what is presented to the users is adapted according to their visualization profile, ability and ultimate purpose(s).

More specifically, the top tier in CAV is the interface through which users can communicate their requirements/feedback and interact with the system. The middle tier is responsible for supporting users to design and generate context-adaptive visualization solutions via two important controllers, i.e. visualization solution controller and visualization context controller. The former manages the creation, modification, transformation, implementation, initialization, execution and retirement of visualization solutions, while the latter focuses on the development lifecycle of context profiles.

With CAV, a visualization solution can be constructed by selecting and integrating appropriate visualization scenario(s) and context profile(s). A visualization scenario can be created by integrating appropriate visualization data, model(s) and solver(s). A visualization model describes how data can be represented and presented by a certain visualization technique, which can be manipulated by visualization solvers (algorithms that manipulate how the visualization model behaves). A visualization context profile can be developed by selecting and mapping appropriate context data, context model(s), evaluation model(s) and context solver(s). A context model is used to define the context where the visualization solution is to be applied, for example, what contextual factors are relevant, their weights in terms of their impact on the visualization solution design, and how they can be structured to describe and represent the visualization context. In contrast, the evaluation model defines the way of how the effectiveness of the generated visualization solution will be measured and monitored. Both the context and evaluation models are manipulated by context solvers. A component view of a visualization solution is presented in Fig. 3. All the context and visualization related data, models, solvers and scenarios are stored in their corresponding resource pools located at the bottom tier.

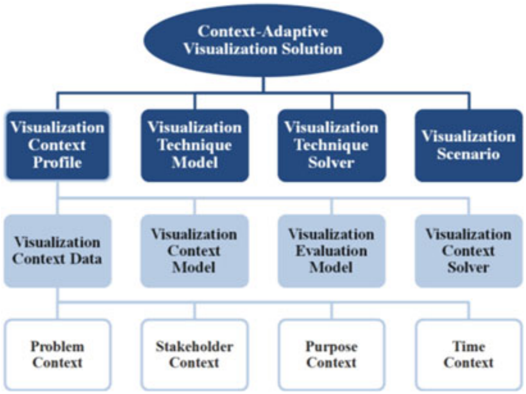

Fig. 3. Context adaptive visualization solution decomposition

4 Implementation

As a proof of concept, we implemented a prototype based on a multi-tier object oriented system architecture which is designed to support the CAV framework. This vertical prototypical system leverages a set of Microsoft technologies, that is, Microsoft Bing map, Windows Presentation Foundation, ADO.NET entity framework, and SQL Server. However, a similar system could be developed by utilizing equivalent technologies from other vendors such as Oracle and IBM. The prototype enables the sensing of contextual changes through accessing a number of historical and/or real-time data streams. The prototype can be applied to help a context-aware system with responding to the contextual changes through creating or adjusting visualization solutions. To demonstrate the support for adapting to the changing context and maintaining visualization effectiveness, we apply the prototype to the case of managing network reliability performance in electricity distribution businesses. This case is representative because it involves a wide range of stakeholders with shared/specific visualization interests, preferences, purposes and requirements, for example, electricity engineers, service/network operators, network pricing analysts, asset investment managers, senior finance managers, etc.

In this section, we delineate the case background Sect. 4.1 and demonstrate the support for adapting to various problem/stakeholder/purpose/time context changes and the associated visualization requirements changes in Sects. 4.2–4.5.

4.1 Case Background

A common requirement of electricity distribution businesses is to measure and analyze their network reliability performance so as to direct maintenance and replacement programmes, meet operational targets, comply with regulatory reporting requirements and enable demonstrably prudent and efficient network asset management decision-making. To support this, electricity distribution companies are often required to monitor and report both the frequency and duration of interruptions through the internationally recognized measures of SAIDI (system average interruption duration index) and SAIFI (system average interruption frequency index). Targets for SAIDI and SAIFI are set by regulatory requirements. One of their strategic goals is to deliver network reliability that meets these targets and also to meet customer expectations, which are reflected in customer service levels. Both operational and management staff within the companies may have the requirement to monitor network faults and investigate their impact on the network so as to direct maintenance efforts and identify trends and anomalies in performance. Apart from this, the companies may be required to disclose their performance against its SAIDI and SAIFI targets in an annual quality compliance statement, which could be subjected to external audit, in order to establish a high level of assurance in the reported information. In some countries like Australia and New Zealand, failure to meet the annual agreed performance targets can incur significant penalties. Therefore, it is quite important to deliver right network fault information to the right users in the companies at the right time and place.

4.2 Problem Context Adaptability

The CAV prototype supports adapting to various problem contexts by creating and manipulating appropriate visualization solutions. For example, a typical problem context in network reliability management is about supporting service/network operations engineers to monitor daily network faults and investigate their impact on the network so as to assist in isolating/removing the faults. Another one is about helping customer relations managers run customer surveys from time to time in order to understand customer experiences/expectations about the network performance and services. To support network fault management, the prototype allows designing and developing visualization solutions showing daily network faults distribution (Fig. 4).

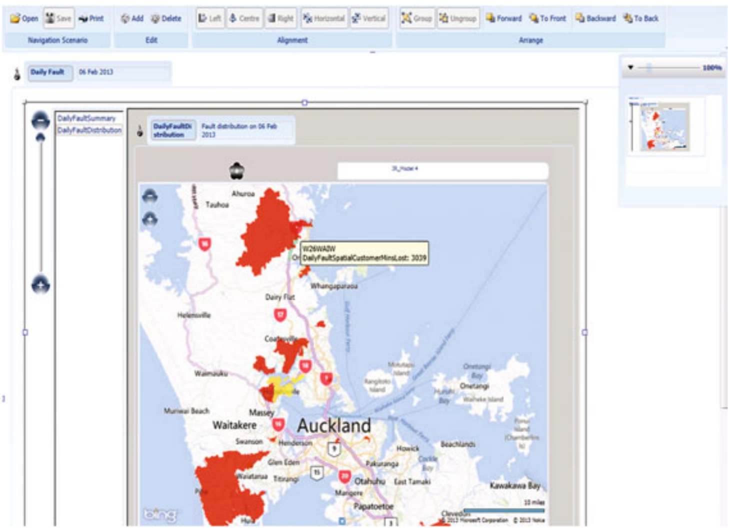

Fig. 4. Daily customer minutes lost by feeder area

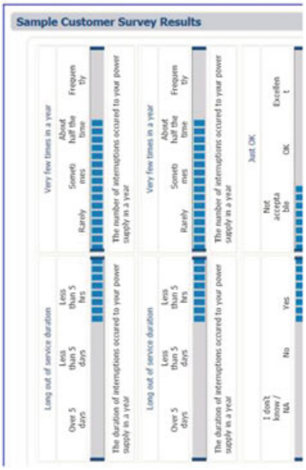

Fig. 5. Sample customer survey results

When the problem context changes to customer satisfaction management, it allows creating visualizations displaying customer survey results (Fig. 5).

4.3 Purpose Context Adaptability

In electricity distribution businesses, monitoring and investigating network faults may aid in fulfilling various purposes (Fig. 6). It can benefit service/network operations engineers to facilitate minimizing risks to the health and safety of people and network equipment and to direct maintenance efforts in a timely manner. It may also assist the

Fig. 6. Daily affected customers by fault type

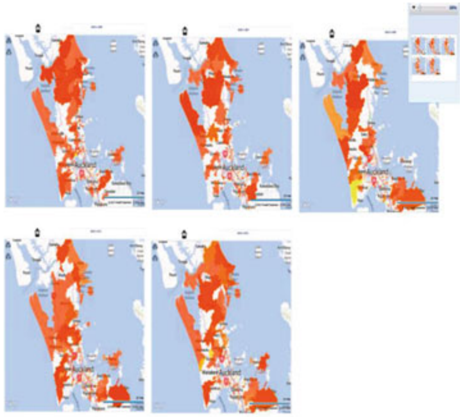

Fig. 7. Yearly SAIDI distributions from 2007 to 2011

senior management to analyze and identify patterns, trends and anomalies in performance including exceptions to service level agreements. With CAV, multiple-layer visualization solutions can be created to support the purpose of service/network operations engineers. For example, it could be helpful to have a two-layer solution presenting both the overview and detailed view of daily network faults. The top layer applies small multiples to represent the number of customers affected by different types of network faults on a selected date (Fig. 7). The size of each bubble represents the affected customers count. In the second layer (Fig. 4), Bing map is utilized to present the distribution of feeder areas affected by the faults and map polygon colors indicate the amount of customer minutes lost in each affected feeder area. The darker the color is, the larger the amount of customer minutes is lost.

When it comes to support the purpose context of discovering patterns of problematic network areas, the prototype can be used to create visualizations allowing users to compare SAIDI distributions cross years (Fig. 8).

4.4 Stakeholder Context Adaptability

CAV can support users with different cognitive and skill acquisition characteristics, prior knowledge and visual preferences. For example, it allows beginner-level users to work with less number of network reliability KPIs during shorter time-periods (normally involving less volumes of performance data) while for proficient users it supports to plot and compare multiple network reliability KPIs in the same timeline viewer (Fig. 9) and zoom in to view relevant details. It also allows users and/or context-aware systems to leverage the efforts already put into developing visualization solutions. Existing visualization solutions can be reused by replacing or adjusting the underlying data, models and solvers settings of the involved visualization and context components to support new visualization requirements.

Fig. 8. Comparing network reliability KPIs of different periods

4.5 Time Context Adaptability

With CAV, users can show network reliability performance in different time periods and drill up/down to display the performance data in long-term/short-term periods. For instance, in the visualization solution below, users can display the distribution of network faults with map polygon color indicating the monthly SAIDI (Fig. 9). The darker the color is, the more significant the monthly SAIDI is to be. If needed, users can drill down to view the relevant daily SAIDI and customer minutes lost that contribute to the monthly KPI.

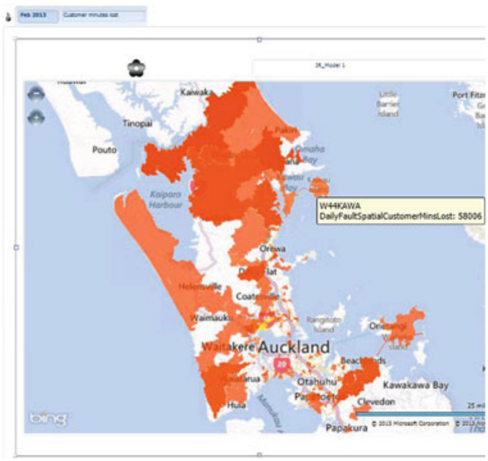

Fig. 9. Monthly SAIDI by feeder area (Color figure online)

5 Conclusion

To achieve high usability and effectiveness, context-aware systems need to provide users a good visibility of the present contextual situations, potential future context alternatives, the decisional problem(s) to be addressed, and how they adapt to contextual changes. These requirements highlight the need of having effective visualization systems embedded in and/or designed separately to support context-aware systems. Such visualization systems need to enable users and/or context-aware systems to flexibly create, manipulate, transform, improve and dispose visualization solutions and maintain their effectiveness under the changing/evolving visualization context. This paper introduces the context adaptive visualization framework, which employs context profiles to model the relevant contextual data and to serve as an input to visualization technique models in order to explicitly mange the impact from contextual changes. CAV supports the flexibility required by developing and maintaining effective visualization solutions through allowing users and/or context-aware systems to integrate and manipulate appropriate visualization components. Furthermore, this paper describes an implementation of CAV through the case of managing and reporting electricity network reliability and demonstrates its support for adapting to various problem/stakeholder/purpose/time context changes and the associated visualization requirement changes. It deserves to be pointed out that the current prototype has only been tested within a limited number of application domains. The application and realization of CAV in a variety of scenarios ranging from business to art to history to engineering to science will be accomplished in our future research.

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