REPRESENTING THE PLANNED vs. AS-BUILT STORY FOR LINEAR PROJECTS IN URBAN ENVIRONMENT USING DATA VISUALIZATION

by

Jehan Zeb

MBA, Sarhad University of Science and Information Technology, 2006

M. Sc. (Transportation Eng.), National University of Sciences & Technology, 1997

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

The Faculty of Graduate Studies

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

November 2007

ABSTRACT

Very large sets of multi-source, multi-dimensional and time varying data are generated during the execution of construction projects, especially large-scale infrastructure projects. Emphasized in this thesis is how data visualization can provide important insights during the planning, implementation and post project analysis phases of linear projects in an urban environment, which are attended by a complex working environment and multiple stakeholders. These insights can lead to enhanced communication and better decision making.

Thesis objectives are four fold: (i) examine how the representation of a schedule using linear planning charts can assist with assessing the quality of a schedule in terms of the construction strategy, communicate schedule intent to projects participants, and assist with telling the as-built story; (ii) explore images useful for representing multi source, multi-dimensional, time varying as-built construction data in support of management functions specifically with regards to communication and decision making; (iii) demonstrate the ability of visual representations of construction data to assist in telling the as-built story of a project in a manner that provides useful insights to project participants; and, (iv) critique the images presented in light of the data visualization principles and interaction tools identified, and suggest improvements as appropriate and possibly other images, including properties desired.

In addressing these objectives, the methodology involved a review of computer science and construction literature as it pertains to data visualization and a case study of a past project which reflected the scale and complexity of planning and executing linear projects in an urban environment. The planned and as-built story were captured from the available data depicting the contractor's perspective in the project's product, process, and as-built views which were replicated in a research software system called REPCON software. This system supports selected data visualization capabilities, which were examined and critiqued as part of this thesis.

It is demonstrated that data visualization is a powerful paradigm for gaining insights into the quality of a project's plan and for understanding a project's as-built performance. Greater benefits could be achieved by exploiting cutting edge visualization tools and by designing and implementing a more comprehensive set of images.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I am indebted in the first instance to Dr. Alan David Russell, who being supervisor of my research work, given me the vision, direction, and recurrent guidance in strategizing and formulating my research work towards accomplishment of the set-forth objectives. His valuable ideas, comments and discussions have led to achieve goals of the research work. Completion of this research work would deem to be impossible without his financial and technical support. I am also grateful to Dr. Sheryl-Staub French, for her valuable teachings and providing us an opportunity in gaining hands on experience in the state-of-the-art 3D and 4D modeling software.

I am also thankful to Chief Executive Officer (CEO), Canada Line and Tenney Chad, Project Manager, Tyam Construction, Canada Line Division, Vancouver, British Columbia, for their extended cooperation in allowing me to take, arrange and incorporate pictures of the construction operations in my thesis work as part of photo-essay preparation.

I am obliged to my colleagues Mingen-En Li and Chau-Ying Chiu, Ph. D. candidates in project and construction management group, for their persistent support in providing me relevant material, holding useful discussions and resolving day to day modeling software related issues. I also pay gratitude to my friend Muhammad Tahir Khan for his valuable comments in writing my thesis.

I pay thanks to all my family members who have strived hard in supporting me financially despite their meager resources.

CO-AUTHORSHIP STATEMENT

The author of this thesis, Jehan Zeb, was responsible for substantial contributions to the content and writing of the co-authored manuscript presented in Chapter 2.

The co-author; Dr. Alan David Russell - Professor, Department of Civil Engineering, and Chair, Computer Integrated Design and Construction - UBC, and Chao-Ying Chiu, Ph. D., Candidate, Project and Construction Management, Department of Civil Engineering, UBC, participated in the development and drafting of ideas and were equal partners with the thesis author in the review and revision of the manuscripts.

Date (2007/11/22)

Signature of Research Supervisor ____

Signature of Thesis Author ____

1 THESIS OVERVIEW

1.1 INTRODUCTION

Projects that involve repetition of activities include construction of highways, rail mass transit systems, railway lines, airport runways, bridges, sewerage systems, water supply systems, high-rise buildings, housing development projects and infrastructure rehabilitation projects wherein construction crews perform work in a linear sequence and move horizontally or vertically from one location/unit of the project to the other (Vanhoucke 2006, Hyari & El-Rayes 2006, Hegazy et al., 2004, El-Rayes 2001, El-Rayes & Moselhi 1998). These projects are most often large in scale, especially transportation ones. For linear projects built in an urban environment, the project focus of this thesis, their complexity is derived from both scale and the natural and man-made environments in which they must be constructed. Due to the complexity and prevailing stakeholder concerns that accompany the implementation of large infrastructure projects in an urban context, a very large volume of data is generated while executing a diverse set of management functions, posing significant challenges to the constructors of such projects.

Thus, tri-partite implementation partners, (relating to client-consultant/designer/architect-contractor), in the construction industry are confronted with several challenges, which include: (i) handling of a very sizeable volume of heterogeneous and often poorly structured or incomplete data; (ii) the integration of the data across diversified construction views to furnish a true picture of inter-related cause and effects; (iii) deducing patterns or insights across project dimensions (Nielsen & Erdogan 2007); and, (iv) effective and efficient decision making based on the patterns or insights generated in a dynamic construction environment where circumstances relating to site conditions including design, weather, access, ground conditions, etc. change rapidly.

Data visualization can play a pivotal role in addressing the foregoing challenges and improving project performance measures in terms of "cost and profit, time, scope, quality, safety and regulatory compliance", (Russell & Udaipurwala 2004). Visualization of data deals with the effective portrayal of construction data to generate insights about the data and to unveil the undiscovered useful information embedded in the very large amount of diversified and assorted construction data that accompanies a project (Keim 1996). This data is heterogeneous in nature, and consists of: (a) textual form, including contract documents, specifications, letters, e-mails, minutes of meeting; (b) quantitative form reflecting schedule data, cost data, site inventory data, and site weather condition data; and, (iii) pictorial form including drawings, photos and videos (Korde et al. 2005 & Chiu and Russell 2007).

Visualization of construction data offers a number of benefits, including: (i) the identification and communication of interdependent relationships across various data items leading to an enhanced ability of the construction team to interpret data and to improve overall decision making (Liston et al. 2000); (ii) amplifying cognition of quantitative date; (iii) improving and verifying the completeness and accuracy of data; (iv) reducing the time spent in comprehending and explaining the information, thereby allowing the construction team to spend more time on reviewing the data to reach the best solutions to the problems at hand; (v) providing managers with information rich overviews regarding the status of various components of the project; (vi) creating a proactive management environment with regards to efficient remedial measures towards adverse circumstances; (vii) reducing ambiguity with which graphs are sometimes created and avoid misconceptions due to inadequacies in data sets; (viii) explaining the divergence and disparity between the planned and as-built stories (Songer et al. 2004, Shaaban et al. 2001, and Pilgrim et al. 2000); and, (xi) assessing the quality of a construction schedule (Russell & Udaipurwala 2000).

Despite the fact that construction of linear projects in an urban context is likely to increase given traffic congestion issues and a concern for sustainable solutions to such problems, including population growth, they are disruptive in nature and impact a diversified set of stakeholders in terms of pollution, safety, environmental, business, and financial issues. Road closures have adverse affects on urban travel with regards to traffic congestion, travel delays, and increased numbers of accidents. Air quality through pollutant emissions and production of dust can pose health hazards for those immediately adjacent or close to the construction corridor. Relocation or removal of utilities during the construction phase of such projects can cause inconvenience to users through the disruption of the function or service they perform. From a financial perspective, such projects may cause neighborhood businesses to lose existing and potential clients due to traffic disruptions and detours, and reduce property values in the neighborhood, either temporarily or on a permanent basis.

A carefully crafted plan of construction along with attendant construction methods can do much to mitigate the foregoing problems. And, when aspects of such a plan cannot be realized because of extenuating circumstances within or beyond the control of project participants, the plan provides the basis for documenting the circumstances or difficulties encountered, the study of which can help to point out strategies for the problems encountered.

In this research work the focus is on how data visualization can help with crafting effective construction plans and gaining insights on problems encountered during a project's construction phase towards effective communication and better decision making.

1.2 DATA VISUALIZATION

The term visualization is defined by Card et al. 1999 as "the use of computer supported, interactive, visual representations of data to amplify cognition", and as "the act or process of interpreting in visual terms or of putting into visible form" (Nielsen and Erdogan, 2007). Our emphasis is on data visualization rather than information visualization which is defined as "the use of computer supported, interactive, visual representations of abstract, non-physically based data to amplify cognition" (Card et al. 1999); or information visualization corresponds to message(s) extracted from data (Korde 2005). Despite the foregoing distinction, we note that the terms data visualization and information visualization tend to be used interchangeably by a number of authors.

During the past two decades considerable progress has been made in the field of visualization specifically pertaining to developing numerous new visual representations/metaphors, interaction methods, software tools and systems (Thomas & Cook 2005). These tools have capabilities to represent and analyze huge data sets employing various interaction techniques to accelerate rapid insights into complex data with the attendant benefits for improved communication (Neilsen and Erdogan 2007), and effective decision making (Songer and Hays 2004). Visual images provide a powerful and persuasive representation of ideas and data which help: (i) illustrate the complex and abstract in a compellingly simple way; (ii) externalize and convey the process of thinking, to transform intangible ideas into tangible information; (iii) reveal ideas/relationships, not just results; and, (iv) engage discussion around the subject, with the aim to communicate the story of events and ideas to the viewer in a sequential manner (Baskinger and Nam 2006).

Realization of these benefits is only possible if the right tool is selected to perform a specific analytic task on a particular data type, using the following basic principles of effective visual representation. According to Norman (1993), these basic principles encompass the following: (i) **appropriateness principle -** a visual representation should only provide the required quantum of information i.e., neither more nor less information than that needed for the task at hand. The provision of too much information complicates the representation, distracting users; (ii) **naturalness principle** - allows the visual representation to be the most effective when there is a match between the user's cognitive model of the information and the information being represented; and, (iii) **matching principle**, wherein effective representation matches with the task being performed by the user. Tversky et al. (2002) has suggested two additional basic principles: (iv) **principle of congruence**, which seeks to make the visual representation more effective through developing the structure and content of the metaphor/visualization in line with the structure and content of the desired mental representation; and, (v) **principle of apprehension,** which seeks to ensure that the structure and content of a visualization should be readily and accurately perceived and comprehended.

Utilizing these basic principles, researchers have tried to develop state-of-the-art visualization techniques based on a range of data types and visual analytic tasks. Several authors have developed taxonomies of visualization techniques based on the type of data and a variety of interactive tools (e.g. pan, zoom, detail on demand, filtering). Shniederman (1996) proposed a taxonomy based on data type(s) along with a second classification schema based on the type of user interactive tools like overview, zoom, filter, and details-on demand, offered by a given visualization technique. The objective of Schneiderman's 2nd classification is to present a clear idea to the user about the specific analytic capabilities of particular visualization tools in support of an explicit analytic task vis-à-vis clustering, comparison, overview-query, and identifying distribution patterns in the data.

In selecting a particular visualization technique, it is of paramount importance to resolve two fundamental issues: (i) the type(s) of data the techniques can support/represent; and, (ii) the kind of user interaction it offers to perform the desired analytic task (Korde et al. 2005). To address these two concerns, Qin et al. (2003) coalesce the two taxonomies proposed by Shneideman into a matrix framework wherein rows represent the type(s) of data, (reflecting 1D, 2D, 3D, multi-dimensional, hierarchical, graph & text/hypertext), and the columns correspond to analytic task, (representing overview-query, comparison, cluster-classification, distribution pattern & dependency correlation analysis), thereby allowing the user to select the most effective visualization technique.

The capability of visualization techniques to perform a variety of analytic tasks distinguishes visual representation from visual analytics. Visual representation is simply the interface or view into the data whereas visual analytics allows the user to analyze the data by way of a dialogue between the analyst and the data. During this dialogue, the analyst observes the data representation, interprets and makes sense of it and then thinks of the next question to ask, essentially formulating a strategy for how to proceed (Card et. al 1999 and Spence 2000). It is pertinent to mention that provision and subsequent use of a set of diversified interactive tools would help the analyst simplify the interpretation process.

There are four primary uses of interaction wherein Card et al. (1999) has identified the following three elementary uses of interactions towards information visualization including; (i) interactions for modifying data transformation. This refers to filtering data to reduce the data information load to have a clear picture in support of a management function. Several common techniques currently used for modifying data transformation include direct manipulation and dynamic queries (Ahlberg 1994); (ii) interactions for modifying data mapping which allows users to interactively change the mapping between the data and its visual representation. Data flow systems and pivot tables are two examples of this technique; and, (iii) interactions for modifying view transformation (navigation) which allows users to navigate through the visual representation by establishing graphical parameters to create views of visual structures.

Interaction techniques for view transformation may range from simple highlighting and selecting objects of interest to more complex and advanced camera control techniques in a 3D environment. View transformations exploit time to extract more information and gain enhanced insight into a visualization by employing three transformations: (i) location probes that use location in the visual structure to look into additional data table information - e.g. details-on-demand and brushing; (ii) view point controls, which allow the visual representation to zoom, pan and clip the view point, techniques of which include “overview + detail” (Shneiderman 1996) wherein two windows are used, the bottom one reflecting the overview of the visual representation and thus providing context while the top window displays the detail of one specific area of the representation; and, (iii) distortion, which is a visual transformation that modifies a visual structure to create focus + context views. It provides the user/analyst with an opportunity to observe both overviews + detail in a single visual structure. Perspective wall and hyperbolic tree are examples of this technique. The hyperbolic tree distorts a large tree layout with a hyperbolic transformation that maps a plan to a circle, shrinking the nodes of the tree far from the root. Thus, overview and details are presented in one view. Distortion is effective when the user can perceive the larger undistorted visual structure through the distortion, whereas it is ineffective when the features and or patterns of use to the user are distorted in a way harmful to the task (Card et al. 1999). Moreover, according to Thomas & Cook (2005), the fourth (iv) use of interaction refers to human information discourse which is needed to support processes such as comparing and categorizing data, extracting and recombining data, creating and testing hypotheses, and annotating data.

A big challenge in visual representation and for the attendant interaction techniques is the issue of handling very large and complex data sets within a single representation. Visual representations should not contain excessive information which can lead to information overload, making it difficult for the user to gain insights into data /information. As emphasized by Thomas and Cook (2005), the techniques employed for the visual representation of data should take into account issues of: (i) "**visual scalability**, the capability of visual representations and visualization tools to display massive data sets effectively; (ii) **information scalability**, the capability to extract the relevant information from massive data streams; (iii) **software scalability**, the capability of the software to accommodate data sets of varying sizes; and, (iv) **analytic scalability**; the capability of the mathematical algorithms to efficiently accommodate large data sets" (Thomas & Cook 2005). It is important to mention that the choice of visual representation affects visual scalability. A state-of-the-art example of a visualization technique which addresses the issue of scalability is "Accordion Drawing", which has been extended to work on trees having up to 15 millions nodes (Beermann et al. 2005).

In the context of this thesis on the visualization of construction data, we seek visual representations that can cope with the volume of data accompanies ever larger projects. Also, we need to identify visualization methods that allow the user to explore the data in a time critical manner while considering factors related to visual limits, human perception limits and information content limits (Thomas & Cook 2005).

1.3 VISUALIZATION IN PROJECT AND CONSTRUCTION MANAGEMENT

Significant opportunities exist for the integration of advanced interactive tools and techniques along with visual analytic tools in support of a diverse range of management functions in the areas of project and construction management. To date, at best only a modest level of effort has been expended by the construction academic community on this topic. Despite the fact that the field of visualization has been instrumental in representing how physical artifacts are to be built from constructability reasoning and construction method workability perspectives (Staub and Fischer 1998), the literature reveals very little about visualization of heterogeneous multi-source, multi-dimensional, time varying data in the project and construction management context.

Songer et al. (2004) developed a formal framework for developing visual strategies for construction project control data based on visualization theory. Visual strategy development should take into account user-scenarios while strategies must incorporate principles of visualization theory, data type and density. Principles of visualization theory may include structuring and filtering, editing for honesty and density, and communicating efficiently. The framework is based on the iterative process of implementing each of these principles while developing data visualization for project control data. The framework starts with structuring the data based on the type of data. "As per visualization theory, structure must be guided by data type", (Shneiderman 1996 and Card et al. 1999). As depicted in the framework as a second step, filtering of the data set is undertaken in response to user scenarios relating to overview, zoom and detail on demand, in order to provide the level of detail required for developing an initial data graphic. Editing of the initial data graphic is an ongoing and iterative process in the framework which is carried out in order to ensure that visual representation reflects the construction data sets accurately, (referred to as honesty), and to monitor the graphic for adequate density of information - i.e. "More information in the same space (data density), is typically desired" (Tufte 1983). Finally the framework concludes with efficient communication of the data sets to ensure enhanced perception of the data. "Visual efficiency is inversely proportional to the number of images needed for the perception of a data set" (Bertin 1983). Moreover, an iterative evaluation of each step is incorporated within the framework to provide feedback on the effectiveness of the visual strategies/data graphics being developed to represent data sets. Based on this framework, four visual representations including scatterplot, linked histogram, hierarchal tree and treemap, have been developed to represent structured cost control data. Treemap representation was found to be the most effective for presenting a number of dimensions (Songer et al. 2004). TreeMaps permit the visualization of huge amounts of hierarchical and categorical data such as budget, sales data and organizational structure data (Zhang and Zhu 1997).

With respect to scheduling data, one of the challenges is to represent an overall view of the entire network so that without looking at the details of each node, managers are still able to identify potential bottlenecks or conflicts. Related work has been described by Russell and

Udaipurwala (2000 & 2002). According to Zhang and Zhu (1997), scheduling with a vision (SWAV) is designed to help project managers and schedulers review and identify bottlenecks, if any, in the construction schedule when thousands of activities and hundreds of resources are involved in the project. When the network becomes really large with thousand of nodes (activities), the situation is complex and it becomes very difficult for the reviewer to trace each and every node, a subset of the network or the entire network as part of the review process towards problem identification. There might be some directions/actions that the scheduler could not observe due to intricacies of the relationships and large data volumes. In this regard, SWAV has the capability to point out the potential directions while keeping the managers aware of how well the action can improve or worsen the situation. There are two principle processors in the SWAV system: (i) a heuristic engine; which takes raw input data, scheduling objectives, resources and their relationships and external constraints to generate regular schedules as Gantt and PERT charts; and, (ii) INFO - visualizer, a processor which represents the regular schedules in visual form as Gantt and PERT charts so that important factors and relationships are depicted with a view to identify global patterns that are hidden in the data to provide directions on improving the schedule at a higher level which means that the scheduler need not look at every activity to have a big picture about the status of the current schedule in terms of critical factors (Zhang and Zhu 1997).

Korde et al. (2005) employed various visualization tools to represent the distribution of change orders in time, location and by project participant. Chiu and Russell (2007) identified key visualization techniques central to the interpretation of heterogeneous construction data including: (i) visual encoding formalism; (ii) visual query; (iii) interaction; and, (iv) linked data views. Russell and Udaipurwala (2000) emphasized the importance of linear planning charts for assessing construction schedule quality, providing a complete overview of a project's schedule in compact form, and representing diversified multi-source, multidimensional and time varying construction data. In addition, they noted the usefulness of 2D and 3D graphs to represent the distribution of resources and to portray problems encountered in time and space.

Liston et al. (2000) evaluated two visualization techniques, ***highlight and overlay*** that visually relate project information, thereby communicating the relationships between project information leading to improvements in the project team's ability to relate project information and in the overall decision making process. "Highlighting is the process of emphasizing, through visual annotation, related sets of information within a view and across multiple views whereas overlay is the process of placing one set of information onto another set of information that results in one merged view", (Liston et al. 2000). Highlighting actions includes selection of project information relating to: (i) **object -** including construction activity, resources, specifications, contract item or cost item; (ii) **spatial region** - selecting a specific region to highlight all related activities or physical components that occur in that region; and, (iii) **temporal region -** selecting a time frame will reflect all related activities or physical components to be performed in that time period. Overlay actions include: (i) overlay of document to document of same type, e.g. overlaying a contractor's Gantt chart over an owner's Gantt chart to compare milestone deviations; (ii) overlay of document to document of different type, e.g. placing 3D model onto a Gantt chart; (iii) overlay of object(s) to documents of same type, e.g. placing a set of activities onto another Gantt chart; and, (iv) overlay of object(s) to a document of different type, e.g. placing a building component onto a Gantt chart. Both of these techniques communicate relationships between project information thus reducing time spent on comparative, descriptive and explanative tasks while enabling project team members to spend more time on reviewing and evaluating the information leading to effective decision making.

In light of the established challenges depicted above and the paucity of research work in the field of data visualization as revealed from the literature review for the disciplines of project and construction management, the opportunity exists to explore ways of visually representing the large scale, heterogeneous construction data sets generated during projects. The specific project context selected is that of linear projects in an urban context, for the reasons given earlier.

1.4 OBJECTIVES

Objectives laid down for the research work on data visualization in the context of linear urban projects include:

1. Examine how the representation of a schedule using linear planning charts can assist with assessing the quality of a schedule in terms of the construction strategy, communicate schedule intent to project participants, and assist with telling the as-built story;
2. Explore images useful for representing multi source, multi-dimensional, time varying as-built construction data in support of management functions specifically with regards to communication and decision making;

3. Demonstrate the ability of visual representations of non-schedule construction data to assist in telling the as-built story of a project in a manner that provides useful insights to project participants; and
4. Critique the images presented in light of the data visualization principles and interaction tools identified, and suggest improvements as appropriate and possibly other images, including properties desired.

1.5 METHODOLOGY

To accomplish the objectives set-forth for this research work, a comprehensive methodology has been formulated in relation to carrying out a detailed case study to depict the significance of visualizing large-scale heterogeneous construction data in support of management functions during the planning, implementation, and post project analysis phases of an urban linear transportation project.

Use is made of the research software system called REPCON, developed by Russell and his research team at the University of British Columbia, Department of Civil Engineering. This system supports linear planning both as a modeling and data visualization environment. In terms of modeling, a project can be represented by way of nine data views which are integrated, allowing associations to be made amongst the different views. Germane to the work described herein are three views. These include: (i) the physical/product view relating what is to be built and the site context; (ii) the process view which pertains to how, when, where and by whom projects are being built; and, (iii) the as-built view which captures what happened, why and actions taken.

Because dealing with the large data sets that accompany construction projects is so important in assessing the practicality / usefulness of visualization tools and images, use has been made of a full-sized project as a case study. And, while sizeable, (an elevated transit project that traverses approximately a 3 km corridor in an urban setting), it is at the lower end of the scale of such projects, some of which can reach 15 – 25 km in length.

The case study data comes from a 3 km segment of the original Advanced Light Rapid Transit Project (ALRT) in Vancouver, British Columbia. The author had access to both as-planned and as-built schedule data, as well as a summary of problems encountered, as seen through the eyes of the contractor. The project highlights the complexity of working in a lengthy corridor in an urban environment, and the types of problems that can be encountered and their consequences in terms of impacting productivity and extending project duration.

The ALRT project being considered here as case study was undertaken between October 1983 and September 1984. From a planning perspective, the work was divided into 5 phases, with a requirement to fulfill 6 client-specified milestone date requirements as shown in table 1.1.

<table>
<tr><th>S. No.</th><th>Phase Range</th><th>Date of Completion</th><th>Finish Milestone (FMS) Range</th><th>Date of Completion</th></tr>
<tr><td>1</td><td>FC755*2 - FC 749*2</td><td>05 Dec 83</td><td>E1: FC755-EC740</td><td>28 Nov 83</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">FC737 - FC654</td><td rowspan="2">31 Jan 84</td><td>E2: FC737-EC677</td><td>16 Jan 84</td></tr>
<tr><td rowspan="2">E3: FC674-EC641</td><td rowspan="2">13 Feb 84</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">FC650*2 - FC608</td><td rowspan="2">01 Mar 84</td></tr>
<tr><td>E4: FC638-FC608</td><td>16Mar 84</td></tr>
<tr><td>4</td><td>EC 605 - EC539</td><td>17 Apr 84</td><td>E5: EC605-EC539</td><td>27 Apr 84</td></tr>
<tr><td>5</td><td>FC533L - FC 458</td><td>22 Jun 84</td><td>E6 : FC 537-FC458</td><td>22 Jun 84</td></tr>
</table>

Table 1.1 Five phases and 06 finish milestones (FMS) with completion dates

The scope of the work treated herein consisted of building 103 foundations and piers in support of a pre-cast beam elevated guideway, with installation of the beams being performed by others. Each phase of the work was modeled using an early implementation of linear scheduling which emphasized work continuity, with the phases being stitched together by using start milestones. The capacity to model the entire project as one integrated schedule did not exist at that time, and schedule graphics were very basic. The schedule generated provided the basis for recording as-built performance in terms of actual start and finish activity dates. Since that time, modeling capabilities have improved dramatically, as has the ability to represent schedule data in visual form. Having said this, the manner in which the original schedule was developed has been largely adhered to. Therefore, in this research work, the as-planned schedule has been recreated, and actual activity dates entered.

To model the product view, (what is to be built), a Physical Component Breakdown Structure (PCBS) of the project is developed. It consisted of the work locations, and a simplified list of project components as shown in figure 1.1(a). As seen in this figure column locations are designated as either fixed (FC or F for short form) or expansion (EC or E). Some locations involved 2 columns and either single or combined footings. They are designated as Fyyy*2 in figure 1.1. Described herein are the project components of the PCBS, which encompass the foundation and pier systems. Foundation systems include: (i) pile foundation sub-system (not present at all locations); (ii) single spread footing foundation sub-system; (iii) combined spread footing sub-system; and (iv) special foundation sub-system. For the work undertaken in this thesis, attention is limited to identifying the work locations, and specifying a limited number of locations attributes as depicted in figure 1.1(b). While not pursued as part of this thesis work, it is recognized that data visualization strategies could be extended to represent location attributes. This is left to future work.

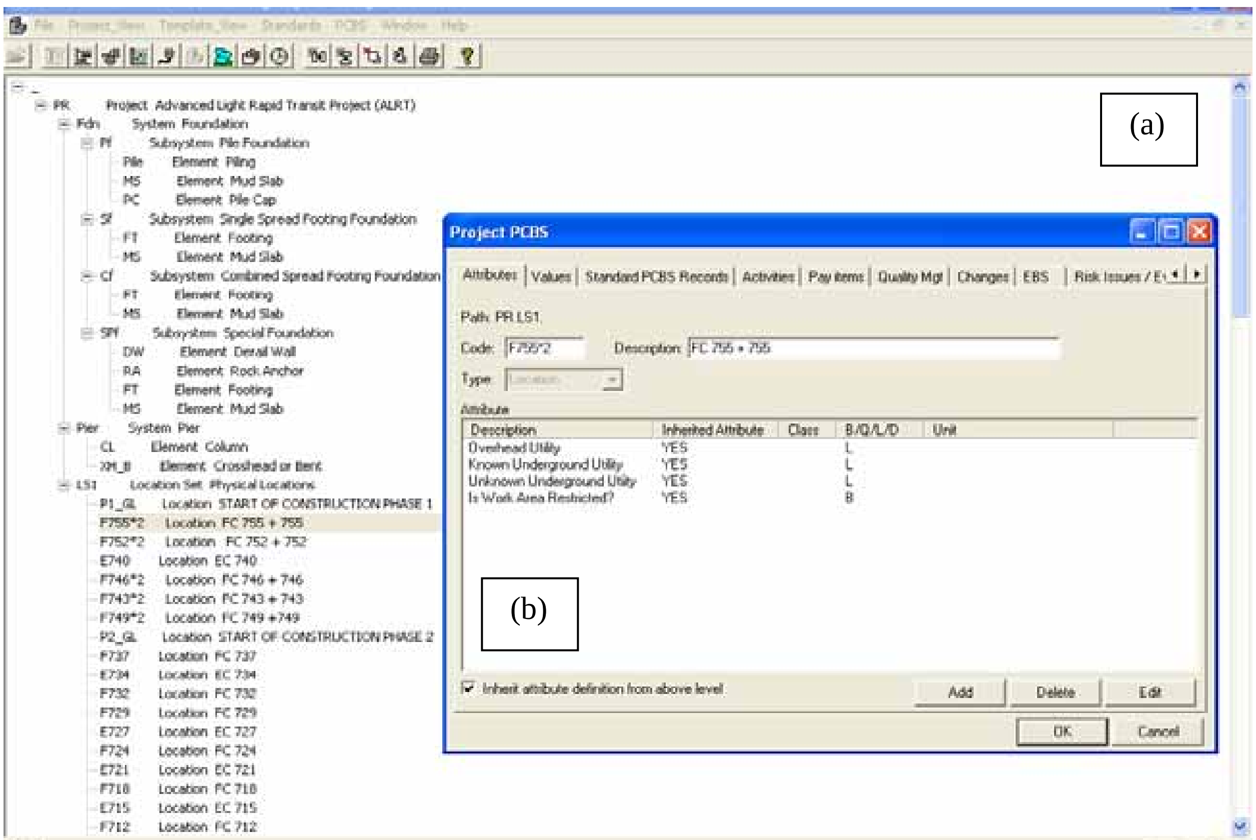


Figure 1.1 Product View – (a) Physical component breakdown structure (PCBS); (b) Specifying column location attributes.

Building the process view (how, when, where and by whom the project is being built), constitutes the second step in representing the project. The original schedule has been recreated based on the then assumptions including: (i) continuity of work for each operation; (ii) completion of the work within the milestone dates set out in the contract document; and, (iii) work is to be executed in an orderly horizontal location sequence which reflects the specific nature of the project, any known constraints regarding access at the outset of the project and the assurance by the client of timely availability and access to individual work sites and lay-down areas. Prior to data entry into the process view, the original project calendar is set to reflect working and non working days, and daily working hours in light of the then regulations and statutory holidays.

Scoping of activities in each phase of the contract follows exactly the original model to ensure compliance with the original schedule, part of which is presented in figure 1.2(a). Scoping of activities includes: (i) survey & layout; (ii) excavation & mud slab; (iii) form & reinforce footings; (iv) pour footings; (v) form columns; (vi) pour columns; (vii) cure & strip columns; (viii) backfill & grade; and, (ix) cleanup. Other occasional activities encompass: (x) driving piles at locations of weak soil conditions; and, (xi) construction of crossheads for expansion columns and a beam (treated as a crosshead) for the expansion bent located at columns EC 471 L&R. Crosshead construction includes form & reinforce, pour, cure & strip and post tension. Figure 1.2(b) shows a photo of completed fixed and expansion columns of the ALRT project. If the project were to be modeled from scratch using current technology, more elegant modeling could be achieved, including the ability to generate a more comprehensive set of insights into the schedule.

As part of the process view, figure 1.2(c) shows production data of a specific repetitive activity describing the sequence of work being adopted to accomplish the activity at various locations, the duration per location and the activity type selected in light of the proposed construction strategy. Figure 1.2(d) illustrates start and finish dates of the repetitive activity, survey & layout at various locations and the responsibility code assigned.

Using the as-built view in REPCON, an effort was made to recreate the daily status of site conditions as well as activity status from the available records maintained by the contractor. As shown in figure 1.3(a), the as-built view automatically displays the planned status of every process view activity using the symbols “s”, “o”, “f”, and “d” to represent start, ongoing, finish and same day activity start and finish, respectively. Actual start and completion dates of all

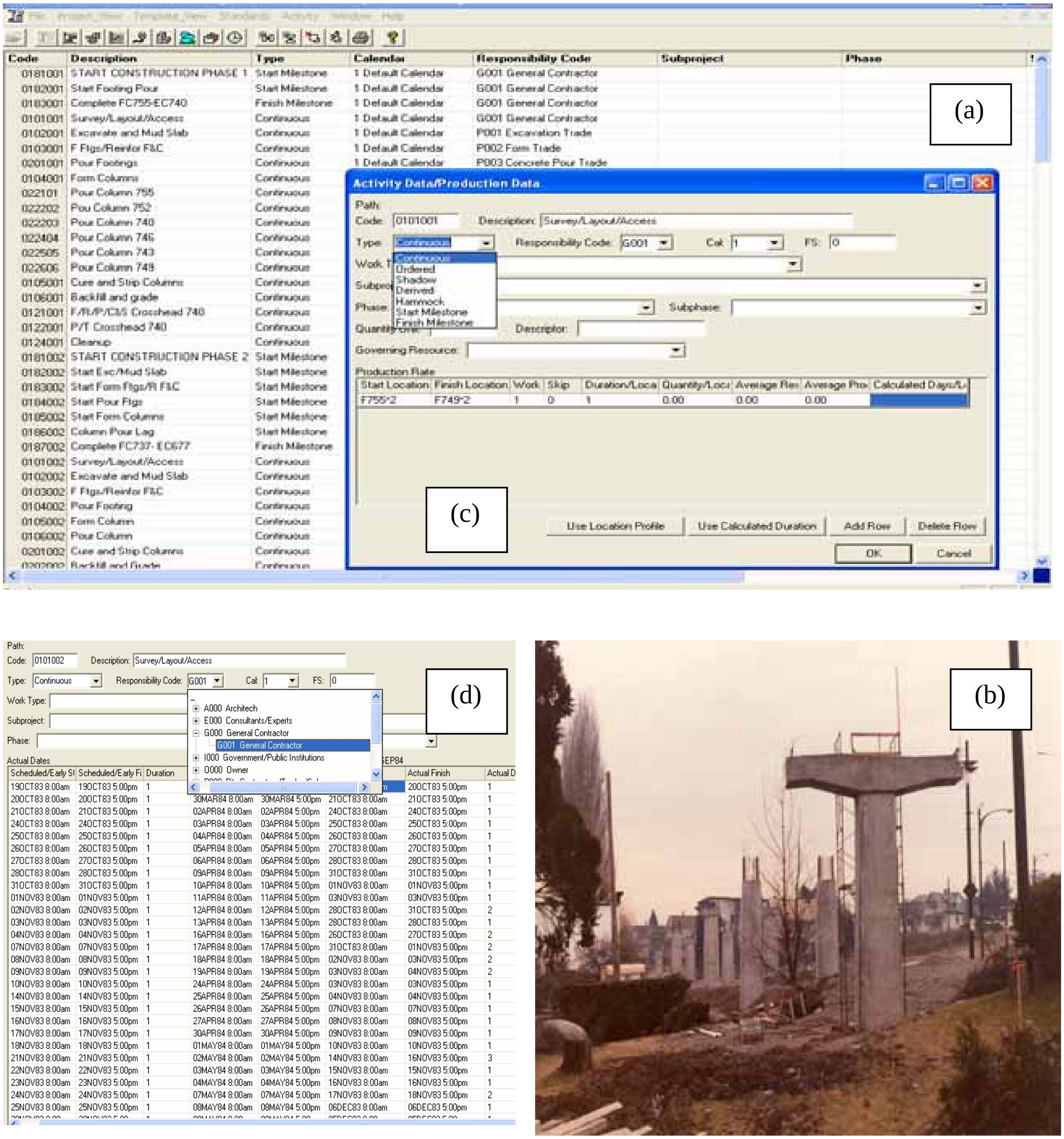


Figure 1.2 Process view – (a) Scoping of project activities by construction phase; (b) Photo of completed fixed and expansion columns; (c) Activity/production data specifying locations worked, production rate and activity type; (d) Planned & actual start & finish dates of activity survey and layout.

activities are then entered into the daily status as reflected in the as-built view from the recorded available data and are symbolized as "S", "O", "F", "P", and "D" to represent actual start, ongoing, finish, postponed and started and finished on the same day. Idle status, "I" is not used because of lack of information. The status, postponed, applies to activities whose actual start is greater than the planned start. Actual start and finish dates of all activities are transmitted to the process view from the as-built view through a batch update command facility.

Daily site environmental data for the time period of interest is retrieved from the Environment Canada web site, as we did not have access to weather data recorded by the contractor, assuming it was. Three parameters including; (i) daily high and low temperatures; (ii) precipitation; and, (iii) wind speed are considered due to their significance for construction operations and performance measures. The values used correspond to those recorded at the Vancouver International Airport meteorological station (VIA Met Station). This weather station is selected as it is the only one that has collected values for all three weather parameters. It is noted that micro climates in the Vancouver area can be highly variable, and there could be differences between weather parameter values experienced at the actual site as compared to those observed at the airport site. As reflected in the weather data for VIA Met Station, if the wind speed is less than 31 km/hr, it is recorded as zero, as there would be little if any impact on the use of the mobile cranes employed for the work. A dialogue box of the environmental conditions recorded in the as-built view is shown in figure 1.3(b).

Problems encountered during the execution phase of the project, as compiled and documented by the contractor, are categorized and coded as shown in figure 1.3(c), which is associated with respective daily status of each activity in the as-built view. An exclamation sign "!" associated with the daily status of the as-built view indicates that one or more problems are associated with a particular activity on that specific day. It is important to mention that contractor's record did not capture problem status on a day-by-day problem basis (at least for the records to which we had access). One of the three scenarios is used in reconstructing the project record: (i) a problem existed up until a specific date (most often the completion date) – the problem may have persisted after that, but it would no longer affect work on the activity (ii) problems that have never resolved and work had to be conducted despite their presence; and, (iii) weekend work. To treat scenario (i), the problem is associated with all days until that specific date (e.g. activity completed), whereas in scenario (ii) the problem is associated with each day until completion of the project. In treating scenario (iii) if an activity spanned a weekend then the status of what is originally a non-working day is changed to working day by incorporating "O, work ongoing". Moreover, if weekend work actually took place (which usually just involved Saturday work), then the actual status is recorded on the Saturday. This typically applied to activities meant to start and finish on Friday. Typically, they are entered as “S”, “F” although recorded and finished on Friday in the actual job record. In the as-built view non-work days are shaded to help with data entry and to gain enhanced comprehension of the calendar interface. Daily status data pertaining to workforce (labor) and equipment levels has not been considered due to non availability of the data.

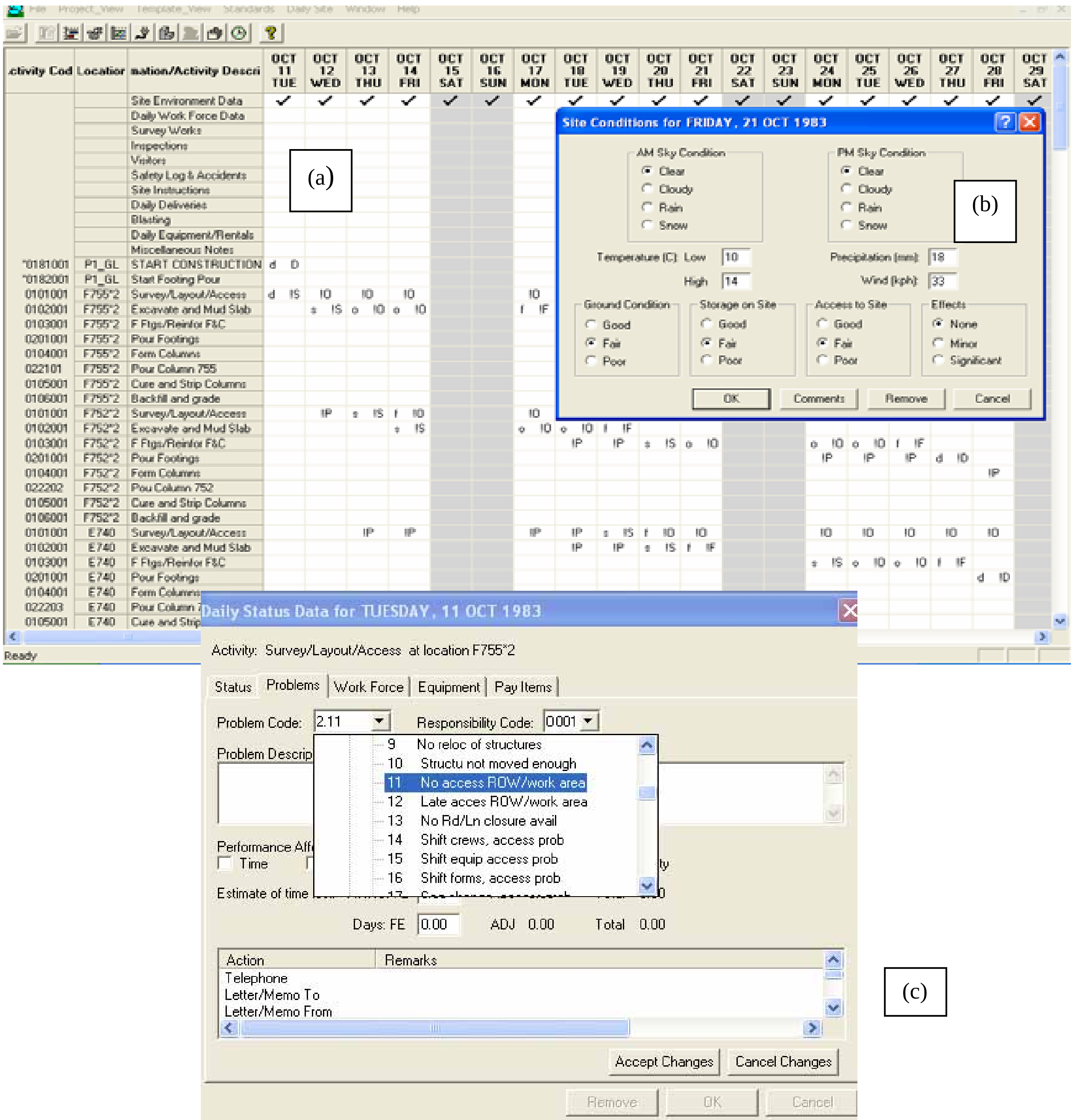


Figure 1.3 As-built view: (a) Capture of planned versus actual daily activity status with problem days flagged; (b) Entry of daily environmental data, (temperature, precipitation & wind/gust speed); (c) Problems coding & assigning of a problem to a specific day/date with

ability to attach a photo or video of status/problem (not done because this material was not available).

1.6 FORM OF THESIS

This thesis consists of 3 chapters including chapter 1 reflecting introduction, literature review, objectives and methodology of the research work. Chapter 2 presents the paper describing various aspects of our core research work. A version of chapter 2 will be submitted for consideration for publication in the Canadian Journal of Civil Engineering. The authorship of this chapter is Jehan Zeb – Graduate student at the Department of Civil Engineering – UBC, and Alan David Russell - Professor, Department of Civil Engineering, and Chair, Computer Integrated Design and Construction – UBC and Chao-Ying Chiu, Ph. D. Candidate, Project and Construction Management, Department of Civil Engineering, UBC. There is a considerable overlap between Chapter 1 and 2, as chapter 2 is meant to stand alone. Chapter 3 is a conclusion & recommendation chapter, which summarizes the research conducted; the contributions made and describe future work.

1.7 REFERENCES

Ahlberg, C. and Shneiderman, B. 1994. Visual information seeking: Tight coupling of dynamic query filters and start-field displays. Proceedings of CHI, ACM Press Boston, pp. 313-317.

Baskinger, M. and Nam, K. C. 2006. Visual narratives: the essential role of imagination in the visualization process. ACM International Conference Proceeding Series Vol. 243. Proceedings of the Asia Pacific Symposium on Information Visualization. Vol. 6, pp. 217-220

Beermann, D., Munzner, T., and Humphreys, G. 2005. Scalable, robust visualization of very large trees. Proceeding of EuroVis 2005, IEEE VGTC Symposium on Visualization, pp.1-8.

Bertin, J. 1983. Semiology of graphics. Madison, WI: University of Wisconsin Press.

Card, S. K., Mackinlay, J. D., and Shneiderman, B. 1999. Readings in information visualization: Using vision to think. Morgan Kaufmann Series in Interactive Technologies, Morgan Kaufmann publisher.

Chiu, C., and Russell, A. D. 2007. Construction process data plus visualization tools equals performance insights. *ASCE Construction Research Congress*, Academic Event Planners, LLC, USA.

El-Rayes, K. 2001. Object-oriented model for repetitive construction scheduling. Journal of Construction Engineering and Management, Vol. 127, No. 3, pp. 199-205.

El-Rayes, K. and Moselhi. O. 1998. Resource-driven scheduling for repetitive activities. Construction Management and Economics, Vol. 16, No. 4, pp. 433-446(14).

Environment Canada Web Site for past environmental/weather data http://www.climate.weatheroffice.ec.gc.ca/advanceSearch/searchHistoricDataStations_e.html

Hegazy, T., Elhakeem, A., and Elbeltagi, E. 2004. Distributed scheduling model for infrastructure networks. Journal of Construction Engineering and Management. Vol. 130, Issue No. 2, pp. 160-167.

Hyari, K. and El-Rayes. K. 2006. Optimal planning and scheduling for repetitive construction projects. Journal of Management in Engineering, Vol. 22, No. 1, pp. 11-19.

Keim, D. A. 1996. Databases and visualization. Proceedings of the ACM SIGMOD International Conference on Management of data, Montreal, Quebec, Canada.

Korde, T., Wang, Y., and Russell, A. D. 2005. Visualization of construction data. 6th Construction Specialty Conference, Toronto, Ontario, Canada. CT-148-1 to CT-148-11.

Liston, K., Fischer, M., and Kunz, J. 2000. Designing and evaluating visualization techniques for construction planning. Computing in Civil and Building Engineering, pp. 1293-1300.

Nielsen, Y. and Erdogan, B. 2007. Level of visualization support for project communication in the Turkish construction industry: A quality function deployment approach. Canadian Journal of Civil Engineering. 34: pp. 19-36.

Norman, D. A. 1993. Things that make us smart. Defending human attributes in the age of the machine. Perseus Books, New York.

Pilgrim, M., Bouchlaghem, D., Loveday, D., and Holmes, M. 2000. Abstract data visualization in the built environment. Proceedings of IEEE International Conference on Information Visualization, London, pp. 126-134.

Qin, Q., Zhou, C., and Pie, T. 2003. Taxonomy of visualization techniques and systems – Concerns between users and developers are different. The State Key Lab of Resources and Environmental Information System, Institute of Geographic Science and Resources Research, Chinese Academy of Sciences, Beijing, China.

Russell, A. D. and Udaipurwala, A. 2000. Assessing the quality of a construction schedule. Proc., of the ASCE Construction Congress VI, Orlando, Florida, USA, 928-937.

Russell, A. D. and Udaipurwala, A. 2002. Construction schedule visualization. Proceedings of the International Workshop on Information Technology in Civil Engineering, Washington D. C., USA, pp. 167-178.

Russell, A. D. and Udaipurwala, A. 2004. Using multiple views to model construction. CIB World Building Congress, Toronto, Canada. 11 pages.

Shaaban, S., Lockley, S., and Elkadi. H. 2001. Information visualization for the architectural practice. Proceedings of the IEEE Fifth International Conference on Information Visualization, London, pp. 43-50.

Shneiderman, B. 1996. The eyes have it: A task by data type taxonomy for information visualization. Proceedings of the IEEE Symposium on Visual Languages. IEEE Computer Society, Los Alamitos, Washington, D. C., pp. 336-343.

Songer, A. D., Hays, B., and North, C. 2004. Multidimensional visualization of project control data. Construction Innovation 2004; 4: pp. 173-190.

Spence, R. 2000. Information visualization. ACM Press, New York.

Staub, S. and Fischer, M. 1998. Constructability reasoning based on a 4D facility model. Structural Engineering World Wide, T191-1 (CD ROM Proceedings), Elsevier Science Ltd.

Thomas, J. J., and Cook, K. A. 2005. Illuminating the path: The research and development agenda for visual Analytics." 1 200.

Tufte, E. R. 1983. The visual display of quantitative information. Cheshire CT: Graphic Press

Tversky, B., Morrison, J. B., and Batrancourt, M. 2002. Animation: can it facilitate. International Journal of Human-Computer Studies, Academic Press Inc., Duluth, Minnesota, 57:247-262..

Vanhoucke, M. 2006. Work continuity constraints in project scheduling. Journal of Construction Engineering and Management, Vol. 132, No. 1, pp. 14-25.

Zhang, P. and Zhu, D. 1997. Information visualization in project management and scheduling. Proceedings of the fourth International Conference on Decision Support Systems, ISDSS'97, Lausanne, Switzerland.

2 REPRESENTING THE PLANNED vs. AS-BUILT STORY FOR LINEAR PROJECTS IN URBAN ENVIRONMENT[1]

2.1 INTRODUCTION

Projects that involve repetition of activities include construction of highways, rail mass transit systems, railway lines, airport runways, bridges, sewerage systems, water supply systems, high-rise buildings, housing development projects and infrastructure rehabilitation projects wherein construction crews perform work in a linear sequence and move horizontally or vertically from one location/unit of the project to the other (Vanhoucke 2006, Hyari & El-Rayes 2006, Hegazy et al., 2004, El-Rayes 2001, El-Rayes & Moselhi 1998). These projects are most often large in scale, especially transportation ones. For linear projects built in an urban environment, the project focus of this thesis, their complexity is derived from both scale and the natural and man-made environments in which they must be constructed. Due to the complexity and prevailing stakeholder concerns that accompany the implementation of large infrastructure projects in an urban context, a very large volume of data is generated while executing a diverse set of management functions, posing significant challenges to the constructors of such projects.

Thus, tri-partite implementation partners, (relating to client-consultant/designer/architect-contractor), in the construction industry are confronted with several challenges, which include: (i) handling of a very sizeable volume of heterogeneous and often poorly structured or incomplete data; (ii) the integration of the data across diversified construction views to furnish a true picture of inter-related cause and effects; (iii) deducing patterns or insights across project dimensions (Nielsen & Erdogan 2007); and, (iv) effective and efficient decision making based on the patterns or insights generated in a dynamic construction environment where circumstances relating to site conditions including design, weather, access, ground conditions, etc. change rapidly.

Data visualization can play a pivotal role in addressing the foregoing challenges and improving project performance measures in terms of "cost and profit, time, scope, quality, safety and regulatory compliance", (Russell & Udaipurwala 2004). Visualization of data deals with the

[1] A version of chapter 2 will be submitted for consideration for publication in the Canadian Journal of Civil Engineering. Zeb, J., Chiu, C. and Russell, A. D. (2007), Representing the planned vs. as-built story for linear projects in urban environment using data visualization. As chapter 2 is meant to stand alone, it contains a significant amount of material from chapter 1.

effective portrayal of construction data to generate insights about the data and to unveil the undiscovered useful information embedded in the very large amount of diversified and assorted construction data that accompanies a project (Keim 1996). This data is heterogeneous in nature, and consists of: (a) textual form, including contract documents, specifications, letters, e-mails, minutes of meeting; (b) quantitative form reflecting schedule data, cost data, site inventory data, and site weather condition data; and, (iii) pictorial form including drawings, photos and videos (Korde et al. 2005 & Chiu and Russell 2007).

Visualization of construction data offers a number of benefits, including: (i) the identification and communication of interdependent relationships across various data items leading to an enhanced ability of the construction team to interpret data and to improve overall decision making (Liston et al. 2000); (ii) amplifying cognition of quantitative date; (iii) improving and verifying the completeness and accuracy of data; (iv) reducing the time spent in comprehending and explaining the information, thereby allowing the construction team to spend more time on reviewing the data to reach the best solutions to the problems at hand; (v) providing managers with information rich overviews regarding the status of various components of the project; (vi) creating a proactive management environment with regards to efficient remedial measures towards adverse circumstances; (vii) reducing ambiguity with which graphs are sometimes created and avoid misconceptions due to inadequacies in data sets; (viii) explaining the divergence and disparity between the planned and as-built stories (Songer et al. 2004, Shaaban et al. 2001, and Pilgrim et al. 2000); and, (xi) assessing the quality of a construction schedule (Russell & Udaipurwala 2000).

Despite the fact that construction of linear projects in an urban context is likely to increase given traffic congestion issues and a concern for sustainable solutions to such problems, including population growth, they are disruptive in nature and impact a diversified set of stakeholders in terms of pollution, safety, environmental, business, and financial issues. Road closures have adverse affects on urban travel with regards to traffic congestion, travel delays, and increased numbers of accidents. Air quality through pollutant emissions and production of dust can pose health hazards for those immediately adjacent or close to the construction corridor. Relocation or removal of utilities during the construction phase of such projects can cause inconvenience to users through the disruption of the function or service they perform. From a financial perspective, such projects may cause neighborhood businesses to lose existing and potential clients due to traffic disruptions and detours, and reduce property values in the neighborhood, either temporarily or on a permanent basis.

A carefully crafted plan of construction along with attendant construction methods can do much to mitigate the foregoing problems. And, when aspects of such a plan cannot be realized because of extenuating circumstances within or beyond the control of project participants, the plan provides the basis for documenting the circumstances or difficulties encountered, the study of which can help to point out strategies for the problems encountered.

In this research work the focus is on how data visualization can help with crafting effective construction plans and gaining insights on problems encountered during a project's construction phase towards effective communication and better decision making.

2.2 DATA VISUALIZATION

The term visualization is defined by Card et al. 1999 as "the use of computer supported, interactive, visual representations of data to amplify cognition", and as "the act or process of interpreting in visual terms or of putting into visible form" (Nielsen and Erdogan, 2007). Our emphasis is on data visualization rather than information visualization which is defined as "the use of computer supported, interactive, visual representations of abstract, non-physically based data to amplify cognition" (Card et al. 1999); or information visualization corresponds to message(s) extracted from data (Korde 2005). Despite the foregoing distinction, we note that the terms data visualization and information visualization tend to be used interchangeably by a number of authors.

During the past two decades considerable progress has been made in the field of visualization specifically pertaining to developing numerous new visual representations/metaphors, interaction methods, software tools and systems (Thomas & Cook 2005). These tools have capabilities to represent and analyze huge data sets employing various interaction techniques to accelerate rapid insights into complex data with the attendant benefits for improved communication (Neilsen and Erdogan 2007), and effective decision making (Songer and Hays 2004). Visual images provide a powerful and persuasive representation of ideas and data which help: (i) illustrate the complex and abstract in a compellingly simple way; (ii) externalize and convey the process of thinking, to transform intangible ideas into tangible information; (iii) reveal ideas/relationships, not just results; and, (iv) engage discussion around the subject, with the aim to communicate the story of events and ideas to the viewer in a sequential manner (Baskinger and Nam 2006).

Realization of these benefits is only possible if the right tool is selected to perform a specific analytic task on a particular data type, using the following basic principles of effective visual representation. According to Norman (1993), these basic principles encompass the following: (i) **appropriateness principle -** a visual representation should only provide the required quantum of information i.e., neither more nor less information than that needed for the task at hand. The provision of too much information complicates the representation, distracting users; (ii) **naturalness principle** - allows the visual representation to be the most effective when there is a match between the user's cognitive model of the information and the information being represented; and, (iii) **matching principle**, wherein effective representation matches with the task being performed by the user. Tversky et al. (2002) has suggested two additional basic principles: (iv) **principle of congruence**, which seeks to make the visual representation more effective through developing the structure and content of the metaphor/visualization in line with the structure and content of the desired mental representation; and, (v) **principle of apprehension,** which seeks to ensure that the structure and content of a visualization should be readily and accurately perceived and comprehended.

Utilizing these basic principles, researchers have tried to develop state-of-the-art visualization techniques based on a range of data types and visual analytic tasks. Several authors have developed taxonomies of visualization techniques based on the type of data and a variety of interactive tools (e.g. pan, zoom, detail on demand, filtering). Shniederman (1996) proposed a taxonomy based on data type(s) along with a second classification schema based on the type of user interactive tools like overview, zoom, filter, and details-on demand, offered by a given visualization technique. The objective of Schneiderman's 2nd classification is to present a clear idea to the user about the specific analytic capabilities of particular visualization tools in support of an explicit analytic task vis-à-vis clustering, comparison, overview-query, and identifying distribution patterns in the data.

In selecting a particular visualization technique, it is of paramount importance to resolve two fundamental issues: (i) the type(s) of data the techniques can support/represent; and, (ii) the kind of user interaction it offers to perform the desired analytic task (Korde et al. 2005). To address these two concerns, Qin et al. (2003) coalesce the two taxonomies proposed by Shneideman into a matrix framework wherein rows represent the type(s) of data, (reflecting

1D, 2D, 3D, multi-dimensional, hierarchical, graph & text/hypertext), and the columns correspond to analytic task, (representing overview-query, comparison, cluster-classification, distribution pattern & dependency correlation analysis), thereby allowing the user to select the most effective visualization technique.

The capability of visualization techniques to perform a variety of analytic tasks distinguishes visual representation from visual analytics. Visual representation is simply the interface or view into the data whereas visual analytics allows the user to analyze the data by way of a dialogue between the analyst and the data. During this dialogue, the analyst observes the data representation, interprets and makes sense of it and then thinks of the next question to ask, essentially formulating a strategy for how to proceed (Card et. al 1999 and Spence 2000). It is pertinent to mention that provision and subsequent use of a set of diversified interactive tools would help the analyst simplify the interpretation process.

There are four primary uses of interaction wherein Card et al. (1999) has identified the following three elementary uses of interactions towards information visualization including; (i) interactions for modifying data transformation. This refers to filtering data to reduce the data information load to have a clear picture in support of a management function. Several common techniques currently used for modifying data transformation include direct manipulation and dynamic queries (Ahlberg 1994); (ii) interactions for modifying data mapping which allows users to interactively change the mapping between the data and its visual representation. Data flow systems and pivot tables are two examples of this technique; and, (iii) interactions for modifying view transformation (navigation) which allows users to navigate through the visual representation by establishing graphical parameters to create views of visual structures.

Interaction techniques for view transformation may range from simple highlighting and selecting objects of interest to more complex and advanced camera control techniques in a 3D environment. View transformations exploit time to extract more information and gain enhanced insight into a visualization by employing three transformations: (i) location probes that use location in the visual structure to look into additional data table information - e.g. details-on-demand and brushing; (ii) view point controls, which allow the visual representation to zoom, pan and clip the view point, techniques of which include "overview + detail" (Shneiderman 1996) wherein two windows are used, the bottom one reflecting the overview of the visual representation and thus providing context while the top window displays the detail of one specific area of the representation; and, (iii) distortion, which is a visual transformation that modifies a visual structure to create focus + context views. It provides the user/analyst with an opportunity to observe both overviews + detail in a single visual structure. Perspective wall and hyperbolic tree are examples of this technique. The hyperbolic tree distorts a large tree layout with a hyperbolic transformation that maps a plan to a circle, shrinking the nodes of the tree far from the root. Thus, overview and details are presented in one view. Distortion is effective when the user can perceive the larger undistorted visual structure through the distortion, whereas it is ineffective when the features and or patterns of use to the user are distorted in a way harmful to the task (Card et al. 1999). Moreover, according to Thomas & Cook (2005), the fourth (iv) use of interaction refers to human information discourse which is needed to support processes such as comparing and categorizing data, extracting and recombining data, creating and testing hypotheses, and annotating data.

A big challenge in visual representation and for the attendant interaction techniques is the issue of handling very large and complex data sets within a single representation. Visual representations should not contain excessive information which can lead to information overload, making it difficult for the user to gain insights into data /information. As emphasized by Thomas and Cook (2005), the techniques employed for the visual representation of data should take into account issues of: (i) "**visual scalability**, the capability of visual representations and visualization tools to display massive data sets effectively; (ii) **information scalability**, the capability to extract the relevant information from massive data streams; (iii) **software scalability**, the capability of the software to accommodate data sets of varying sizes; and, (iv) **analytic scalability**; the capability of the mathematical algorithms to efficiently accommodate large data sets" (Thomas & Cook 2005). It is important to mention that the choice of visual representation affects visual scalability. A state-of-the-art example of a visualization technique which addresses the issue of scalability is "Accordion Drawing", which has been extended to work on trees having up to 15 millions nodes (Beermann et al. 2005).

In the context of this thesis and the visualization of construction data, we seek visual representations that can cope with the volume of data accompanies ever larger projects. Also, we need to identify visualization methods that allow the user to explore the data in a time critical manner while considering factors related to visual limits, human perception limits and information content limits (Thomas & Cook 2005).

2.3 VISUALIZATION IN PROJECT AND CONSTRUCTION MANAGEMENT

Significant opportunities exist for the integration of advanced interactive tools and techniques along with visual analytic tools in support of a diverse range of management functions in the areas of project and construction management. To date, at best only a modest level of effort has been expended by the construction academic community on this topic. Despite the fact that the field of visualization has been instrumental in representing how physical artifacts are to be built from constructability reasoning and construction method workability perspectives (Staub and Fischer 1998), the literature reveals very little about visualization of heterogeneous multi-source, multi-dimensional, time varying data in the project and construction management context.

Songer et al. (2004) developed a formal framework for developing visual strategies for construction project control data based on visualization theory. Visual strategy development should take into account user-scenarios while strategies must incorporate principles of visualization theory, data type and density. Principles of visualization theory may include structuring and filtering, editing for honesty and density, and communicating efficiently. The framework is based on the iterative process of implementing each of these principles while developing data visualization for project control data. The framework starts with structuring the data based on the type of data. "As per visualization theory, structure must be guided by data type" (Shneiderman 1996 & Card et al. 1999). As depicted in the framework as a second step, filtering of the data set is undertaken in response to user scenarios relating to overview, zoom and detail on demand, in order to provide the level of detail required for developing an initial data graphic. Editing of the initial data graphic is an ongoing and iterative process in the framework which is carried out in order to ensure that visual representation reflects the construction data sets accurately, (referred to as honesty), and to monitor the graphic for adequate density of information - i.e. "More information in the same space (data density), is typically desired" (Tufte 1983). Finally the framework concludes with efficient communication of the data sets to ensure enhanced perception of the data. "Visual efficiency is inversely proportional to the number of images needed for the perception of a data set" (Bertin 1983). Moreover, an iterative evaluation of each step is incorporated within the framework to provide feedback on the effectiveness of the visual strategies/data graphics being developed to represent data sets. Based on this framework, four visual representations including scatterplot, linked histogram, hierarchal tree and treemap, have been developed to represent structured cost control data. Treemap representation was found to be the most effective for presenting a number of dimensions (Songer et al. 2004). TreeMaps permit the visualization of huge amounts of hierarchical and categorical data such as budget, sales data and organizational structure data (Zhang and Zhu 1997).

With respect to scheduling data, one of the challenges is to represent an overall view of the entire network so that without looking at the details of each node, managers are still able to identify potential bottlenecks or conflicts. Related work has been described by Russell and Udaipurwala (2000 & 2002). According to Zhang and Zhu (1997), scheduling with a vision (SWAV) is designed to help project managers and schedulers review and identify bottlenecks, if any, in the construction schedule when thousands of activities and hundreds of resources are involved in the project. When the network becomes really large with thousand of nodes (activities), the situation is complex and it becomes very difficult for the reviewer to trace each and every node, a subset of the network or the entire network as part of the review process towards problem identification. There might be some directions/actions that the scheduler could not observe due to intricacies of the relationships and large data volumes. In this regard, SWAV has the capability to point out the potential directions while keeping the managers aware of how well the action can improve or worsen the situation. There are two principle processors in the SWAV system: (i) a heuristic engine; which takes raw input data, scheduling objectives, resources and their relationships and external constraints to generate regular schedules as Gantt and PERT charts; and, (ii) INFO - visualizer, a processor which represents the regular schedules in visual form as Gantt and PERT charts so that important factors and relationships are depicted with a view to identify global patterns that are hidden in the data to provide directions on improving the schedule at a higher level which means that the scheduler need not look at every activity to have a big picture about the status of the current schedule in terms of critical factors (Zhang and Zhu 1997).

Korde et al. (2005) employed various visualization tools to represent the distribution of change orders in time, location and by project participant. Chiu and Russell (2007) identified key visualization techniques central to the interpretation of heterogeneous construction data including: (i) visual encoding formalism; (ii) visual query; (iii) interaction; and, (iv) linked data views. Russell and Udaipurwala (2000) emphasized the importance of linear planning charts for assessing construction schedule quality, providing a complete overview of a project's schedule in compact form, and representing diversified multi-source, multidimensional and time varying construction data. In addition, they noted the usefulness of 2D and 3D graphs to represent the distribution of resources and to portray problems encountered in time and space.

Liston et al. (2000) evaluated two visualization techniques, ***highlight and overlay*** that visually relate project information, thereby communicating the relationships between project information leading to improvements in the project team's ability to relate project information and in the overall decision making process. Highlighting is the process of emphasizing, through visual annotation, related sets of information within a view and across multiple views whereas overlay is the process of placing one set of information onto another set of information that results in one merged view. Highlighting actions includes selection of project information relating to: (i) **object -** including construction activity, resources, specifications, contract item or cost item; (ii) **spatial region -** selecting a specific region to highlight all related activities or physical components that occur in that region; and, (iii) **temporal region -** selecting a time frame will reflect all related activities or physical components to be performed in that time period. Overlay actions include: (i) overlay of document to document of same type, e.g. overlaying a contractor's Gantt chart over an owner's Gantt chart to compare milestone deviations; (ii) overlay of document to document of different type, e.g. placing 3D model onto a Gantt chart; (iii) overlay of object(s) to documents of same type, e.g. placing a set of activities onto another Gantt chart; and, (iv) overlay of object(s) to a document of different type, e.g. placing a building component onto a Gantt chart. Both of these techniques communicate relationships between project information thus reducing time spent on comparative, descriptive and explanative tasks while enabling project team members to spend more time on reviewing and evaluating the information leading to effective decision making. The summary of the visualization and interactive techniques is presented in table 2.1.

In light of the established challenges depicted above and the paucity of research work in the field of data visualization as revealed from the literature review for the disciplines of project and construction management, the opportunity exists to explore ways of visually representing the large scale, heterogeneous construction data sets generated during projects. The specific project context selected is that of linear projects in an urban context, for the reasons given earlier.

Techniques cited in literature review	Definitions of the techniques	Techniques used in this research work
Visual encoding formalism	It refers to the approach/manner, in terms of visual substrate, visual/graphical marks (points, lines, area) and retinal/graphical properties (size, shape, color, texture), in which data is mapped into visual structures, upon which images on a screen are built.	Yes
Visual Query (Direct manipulation or dynamic query)	Visual query refers to questioning or interrogating the visual representation either through human computer graphical interface (dynamic query) or by direct manipulation (highlighting, labeling, deleting).	No
Interaction techniques for view transformation: **1. Location probes**	**1. Location probes** use location in the visual structure to look into additional data table information, e.g. **Brushing:** allows users to highlight information of interest in visualization.	Yes
2. View point controls	**2. View point controls** are view transformations which allow the visual representations to zoom, pan, and clip the view points. **Zoom:** is to magnify or shrink the representation/visualization. **Pan:** allows the user to move the representation in the spatial substrate without zoom in/out.	Yes
3. Overview + detail	**3. Overview + detail** is that two windows are used together, the bottom one reflecting the overview of the visual representation, thus providing context while the top window displays the detail/magnified focus of one specific area of the visualization. Overview acts as a control widget to change the detail view.	Yes
4. Distortion	**4. Distortion is** visual transformation that modifies a visual structure to create focus + context views where overview and details are combined in a single visual representation. Examples are hyperbolic tree and perspective wall. **Focus + context:** it allows the overview and details in a single visual representation. In perspective wall, front portion of the wall reflecting the details to act as focus and the bent part of wall representing the overview of information and acting as context for information.	No
Interaction techniques for data transformation	**Filtering:** This refers to sorting huge data sets to select a sub set of the data based on desired selection criteria.	Yes
Linked data views and Highlight	Highlighting is the process of emphasizing, through visual annotation, related sets of information within a view and across multiple views.	No
Overlay	Overlay is the process of placing one set of information onto another set of information that results in one merged view.	Yes

Table 2.1 Summary of visualization and interactive techniques

2.4 OBJECTIVES

Objectives laid down for the research work on data visualization in the context of linear urban projects include:

1. Examine how the representation of a schedule using linear planning charts can assist with assessing the quality of a schedule in terms of the construction strategy, communicate schedule intent to project participants, and assist with telling the as-built story;
2. Explore images useful for representing multi source, multi-dimensional, time varying as-built construction data in support of management functions specifically with regards to communication and decision making;
3. Demonstrate the ability of visual representations of non-schedule construction data to assist in telling the as-built story of a project in a manner that provides useful insights to project participants; and
4. Critique the images presented in light of the data visualization principles and interaction tools identified, and suggest improvements as appropriate and possibly other images, including properties desired.

2.5 OVERVIEW OF THE CASE STUDY

To illustrate the benefits that can be derived from and issues surrounding the effective visual representation of the large data sets that accompany construction projects, use has been made of a full-sized project as a case study. And, while sizeable, (an elevated transit project that traverses approximately a 3 km corridor in an urban setting), it is at the lower end of the scale of such projects, some of which can reach 15 – 25 km in length. The case study data comes from a 3 km segment of the original Advanced Light Rapid Transit Project (ALRT) in Vancouver, British Columbia. The author had access to both as-planned and as-built schedule data, as well as a summary of problems encountered, as seen through the eyes of the contractor. The project highlights the complexity of working in a lengthy corridor in an urban environment, and the types of problems that can be encountered and their consequences in terms of impacting productivity and extending project duration.

The ALRT project being considered here as case study was undertaken between October 1983 and September 1984. From a planning perspective, the work was divided into 5 phases, with a requirement to fulfill 6 client-specified milestone date requirements as presented in table 2.2.

S. No.	**Phase Range**	**Date of Completion**	**Finish Milestone (FMS) Range**	**Date of Completion**
1	FC755*2 - FC 749*2	05 Dec 83	E1: FC755-EC740	28 Nov 83
2	FC737 - FC654	31 Jan 84	E2: FC737-EC677	16 Jan 84
			E3: FC674-EC641	13 Feb 84
3	FC650*2 - FC608	01 Mar 84	E4: FC638-FC608	16Mar 84
4	EC 605 - EC539	17 Apr 84	E5: EC605-EC539	27 Apr 84
5	FC533L - FC 458	22 Jun 84	E6 : FC 537-FC458	22 Jun 84

Table 2.2 Five phases and 06 finish milestones (FMS) with completion dates

The scope of the work treated herein consisted of building 103 foundations and piers in support of a pre-cast beam elevated guideway, with installation of the beams being performed by others. Each phase of the work is modeled using an early implementation of linear scheduling which emphasized work continuity, with the phases being stitched together by using start milestones. The capacity to model the entire project through REPCON system as one integrated schedule did not exist at that time, and schedule graphics were very basic. The schedule generated provided the basis for recording as-built performance in terms of actual start and finish activity dates. Since that time, modeling capabilities have improved dramatically, as has the ability to represent schedule data in visual form. Having said this, the manner in which the original schedule is developed has been largely adhered to. Therefore, in this research work, the as-planned schedule has been recreated, and actual activity dates entered.

Germane to the research work described herein is the treatment of three views in the REPCON software system. These include: (i) the physical/product view relating what is to be built and the site context; (ii) the process view which pertains to how, when, where and by whom projects are being built; and, (iii) the as-built view which captures what happened, why and actions taken.

To model the product view, (what is to be built), a Physical Component Breakdown Structure (PCBS) of the project is developed. It consisted of the work locations, and a simplified list of project components as shown in figure 2.1(a). As seen in this figure column locations are designated as either fixed (FC or F for short form) or expansion (EC or E). Some locations involved 2 columns and either single or combined footings. They are designated as Fyyy*2 in figure 2.1. Described herein are the project components of the PCBS, which encompass the foundation and pier systems. Foundation systems include: (i) pile foundation sub-system (not present at all locations); (ii) single spread footing foundation sub-system; (iii) combined spread footing sub-system; and (iv) special foundation sub-system. For the work undertaken in this thesis, attention is limited to identifying the work locations, and specifying a limited number of locations attributes as depicted in figure 2.1(b). While not pursued as part of this thesis work, it is recognized that data visualization strategies could be extended to represent location attributes. This is left to future work.

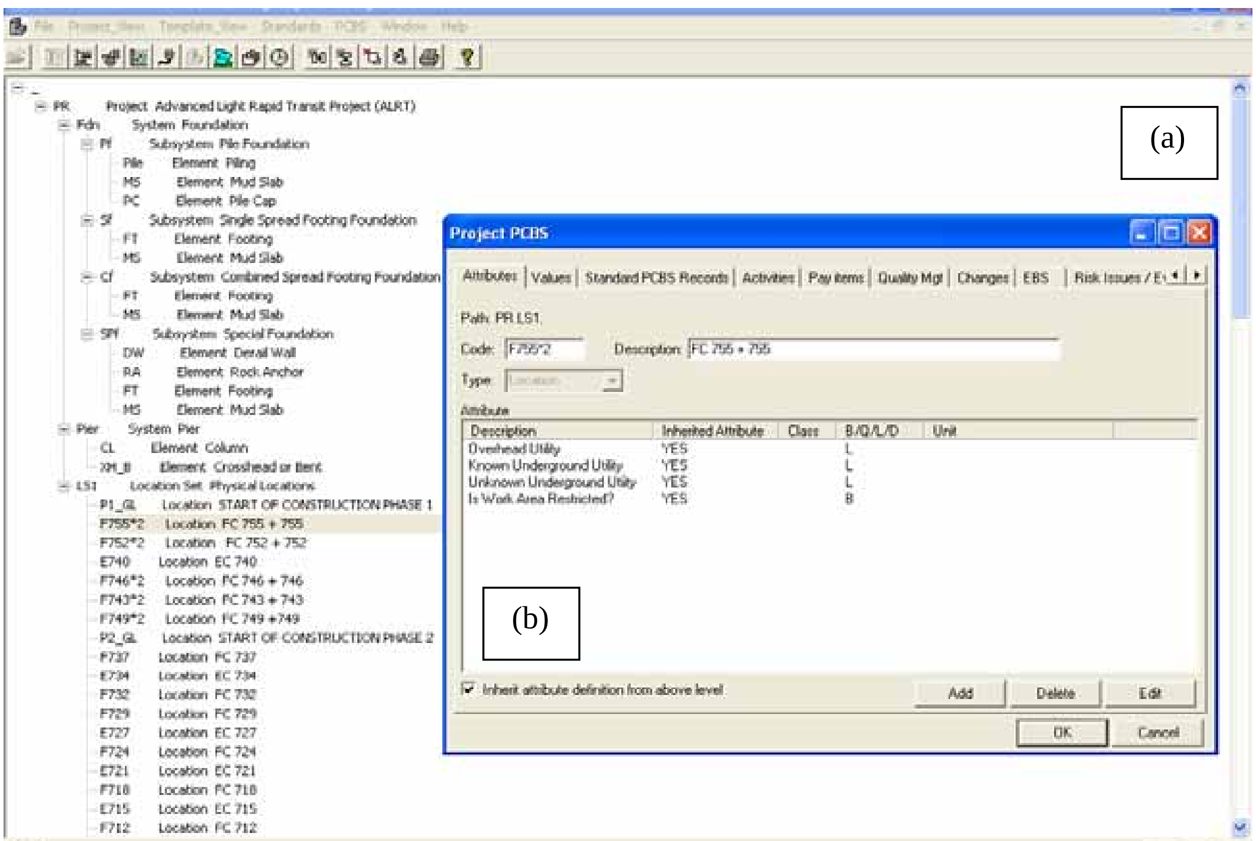


Figure 2.1 Product View – (a) Physical component breakdown structure (PCBS); (b) Specifying column location attributes.

Building the process view (how, when, where and by whom the project is being built), constitutes the second step in representing the project. The original schedule has been recreated based on the then assumptions including: (i) continuity of work for each operation; (ii) completion of the work within the milestone dates set out in the contract document; and, (iii) work is to be executed in an orderly horizontal location sequence which reflects the specific nature of the project, any known constraints regarding access at the outset of the project and the assurance by the client of timely availability and access to individual work sites and lay-down areas. Prior to data entry into the process view, the original project calendar is set to reflect working and non working days, and daily working hours in light of the then regulations and statutory holidays.

Scoping of activities in each phase of the contract follows exactly the original model to ensure compliance with the original schedule, part of which is presented in figure 2.2(a). Scoping of activities includes: (i) survey & layout; (ii) excavation & mud slab; (iii) form & reinforce footings; (iv) pour footings; (v) form columns; (vi) pour columns; (vii) cure & strip columns; (viii) backfill & grade; and, (ix) cleanup. Other occasional activities encompass: (x) driving piles at locations of weak soil conditions; and, (xi) construction of crossheads for expansion columns and a beam (treated as a crosshead) for the expansion bent located at columns EC 471 L&R. Crosshead construction includes form & reinforce, pour, cure & strip and post tension. Figure 2.2(b) shows a photo of completed fixed and expansion columns of the ALRT project. If the project is to be modeled from scratch using current technology, more elegant modeling could be achieved, including the ability to generate a more comprehensive set of insights into the schedule.

As part of the process view, figure 2.2(c) shows production data of a specific repetitive activity describing the sequence of work being adopted to accomplish the activity at various locations, the duration per location and the activity type selected in light of the proposed construction strategy. Figure 2.2(d) illustrates start and finish dates of the repetitive activity, survey & layout at various locations and the responsibility code assigned.

Using the as-built view in REPCON, an effort was made to recreate the daily status of site conditions as well as activity status from the available records maintained by the contractor. As shown in figure 2.3(a), the as-built view automatically displays the planned status of every process view activity using the symbols “s”, “o”, “f”, and “d” to represent start, ongoing, finish and same day activity start and finish, respectively. Actual start and completion dates of all

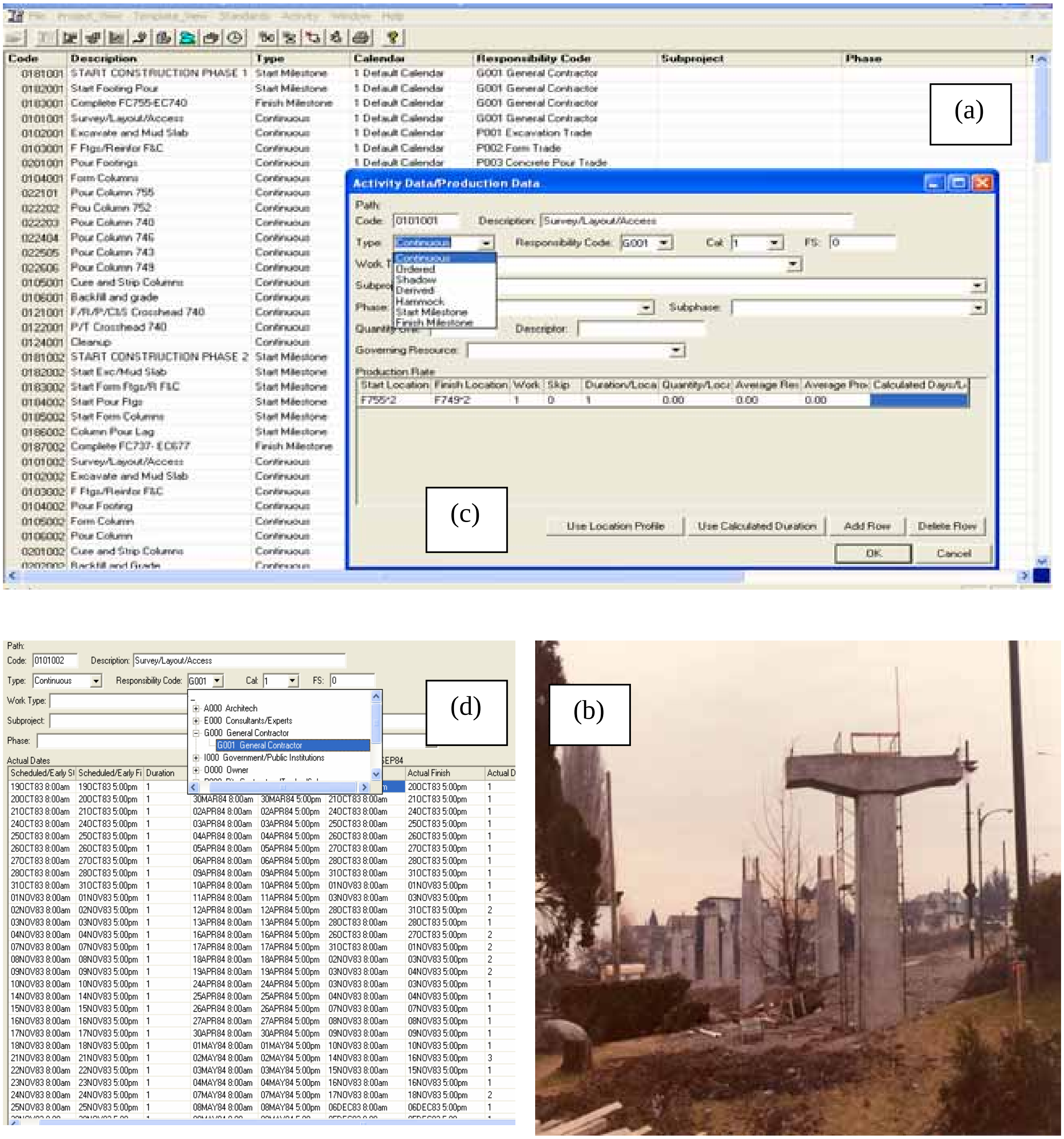


Figure 2.2 Process view – (a) Scoping of project activities by construction phase; (b) Photo of completed fixed and expansion columns; (c) Activity/production data specifying locations worked, production rate and activity type; (d) Planned & actual start & finish dates of activity survey and layout.

activities are then entered into the daily status as reflected in the as-built view from the recorded available data and are symbolized as “S”, “O”, “F”, “P”, and “D” to represent actual start, ongoing, finish, postponed and started and finished on the same day. Idle status, “I” is not used because of lack of information. The status, postponed, applies to activities whose actual start is greater than the planned start. Actual start and finish dates of all activities are transmitted to the process view from the as-built view through a batch update command facility. Daily site environmental data for the time period of interest is retrieved from the Environment Canada web site, as we did not have access to weather data recorded by the contractor, assuming it was. Three parameters including; (i) daily high and low temperatures; (ii) precipitation; and, (iii) wind speed are considered due to their significance for construction operations and performance measures. The values used correspond to those recorded at the Vancouver International Airport meteorological station (VIA Met Station). This weather station is selected as it is the only one that has collected values for all three weather parameters. It is noted that micro climates in the Vancouver area can be highly variable, and there could be differences between weather parameter values experienced at the actual site as compared to those observed at the airport site. As reflected in the weather data for VIA Met Station, if the wind speed is less than 31 km/hr, it is recorded as zero, as there would be little if any impact on the use of the mobile cranes employed for the work. A dialogue box of the environmental conditions recorded in the as-built view is shown in figure 2.3(b).

Problems encountered during the execution phase of the project, as compiled and documented by the contractor, are categorized and coded as shown in figure 2.3(c), which is associated with respective daily status of each activity in the as-built view. An exclamation sign "!" associated with the daily status of the as-built view indicates that one or more problems are associated with a particular activity on that specific day. It is important to mention that contractor's record did not capture problem status on a day-by-day problem basis (at least for the records to which we had access). One of the three scenarios is used in reconstructing the project record: (i) a problem existed up until a specific date (most often the completion date) – the problem may have persisted after that, but it would no longer affect work on the activity (ii) problems that have never resolved and work had to be conducted despite their presence; and, (iii) weekend work. To treat scenario (i), the problem is associated with all days until that specific date (e.g. activity completed), whereas in scenario (ii) the problem is associated with each day until completion of the project. In treating scenario (iii) if an activity spanned a weekend then the status of what is originally a non-working day is changed to working day by incorporating "O, work ongoing". Moreover, if weekend work actually took place (which usually just involved Saturday work), then the actual status is recorded on the Saturday. This typically applied to activities meant to start and finish on Friday. Typically, they are entered as "S", "F" although recorded and finished on Friday in the actual job record. In the as-built view non-work days are shaded to help with data entry and to gain enhanced comprehension of the calendar interface. Daily status data pertaining to workforce (labor) and equipment levels has not been considered due to non availability of the data.

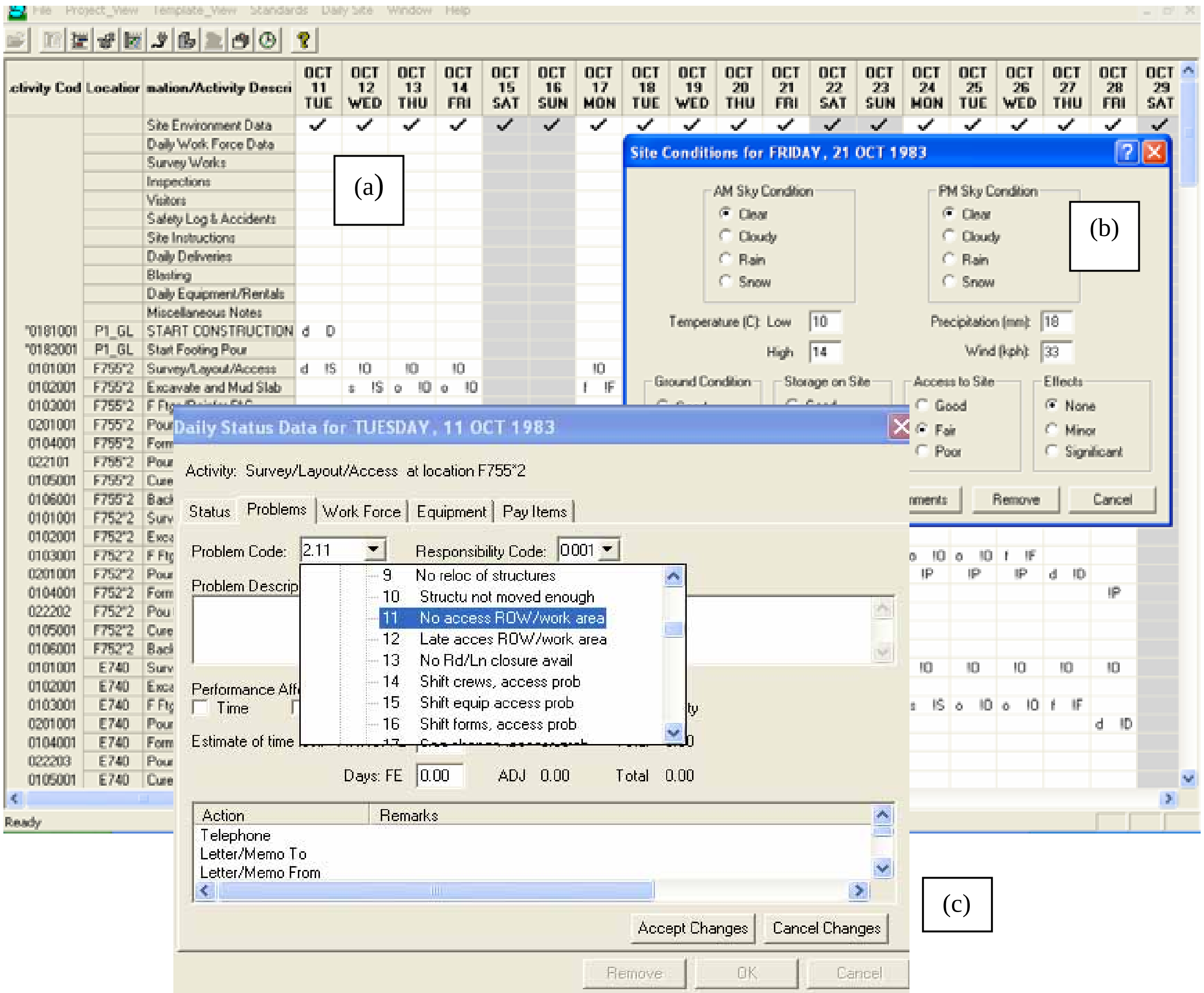


Figure 2.3 As-built view: (a) Capture of planned versus actual daily activity status with problem days flagged; (b) Entry of daily environmental data, (temperature, precipitation & wind/gust speed); (c) Problems coding & assigning of a problem to a specific day/date with ability to attach a photo or video of status/problem (not done because this material was not available).

2.6 VISUAL IMAGES FOR PLANNING AND AS-BUILT SCHEDULE DATA

Visual images related to objectives 1 through 3 are presented in the following two subsections which deal with the use of linear planning schedule representation and visual images of as-built construction data, respectively.

2.6.1 LINEAR PLANNING SCHEDULE REPRESENTATION (OBJECTIVE 1)

The focus of this subsection is on the use of linear planning graphics for assessing the quality of a schedule and for telling part of the as-built story. Work described in this thesis is an extension to the research work undertaken by Russell and Udaipurwala (2000), with regards to assessing quality of a schedule in the planning phase of a project. An attempt has been made in this thesis work to represent the planned schedule in conjunction with a pictorial representation of the construction corridor and construction methods adopted, thereby further enhancing the opportunity to assess schedule quality. While not described herein, it is important to note that the images presented are generated from an interactive planning environment which allows for their direct manipulation in terms of content, time and space zooming, and direct modification of the schedule, its recalculation and refreshing of the linear planning representation. Thus, the images presented are not just static representations of the schedule.

The representation via linear planning of a construction schedule of a large scale linear project is of paramount importance in assessing the quality of the plan as a function of the construction strategy to be adopted for project execution. Such a representation, especially if combined with satellite or other pictorial representations of the construction corridor and methods to be used clearly communicates the intricacies involved, including, traffic management, utilities relocation, land acquisition, access to the work site, environmental issues and safety management. Together, such representations help construction personnel and others envisage how the work will flow in an orderly sequence as depicted in figures 2.4 and 2.5, for elevated guideway and cut and cover construction work in an urban environment, respectively. All of the prominent steps involved in both design solutions are presented in these figures in order to emphasize the importance of being able to work in an ordered location sequence. Disruption of work at any step in the process would interrupt the construction cycle time, which could lead to significant idle work time for both labor and equipment, and or costly movements of resources to out of sequence locations to maintain momentum. Such out of sequence work can disturb supply chain management specifically with regards to pre-cast operations, lead to the need to manage multiple work faces, complicate the coordination of utility relocation and site acquisition, and pose inconvenience to road users, local residents, line agencies and the business community.

In terms of the attributes required of a good “quality” schedule especially in an urban environment, the linear planning chart shown in figure 2.6 portrays several of the factors that contribute to an effective construction strategy. First, the work is executed in an ordered work location sequence. Next, it is evident from the figure that production rates have been balanced

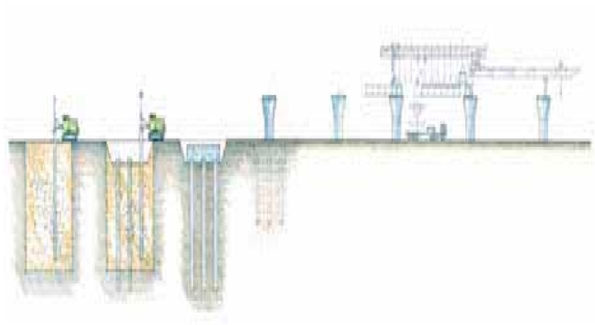


Photo 1. Elev. guideway construction method[2]	Photo 2. Drilling of piles
	
Photo 3. Pile cap footing poured	Photo 4. Pile cap rebar fabrication
	
Photo 5. Column pouring[2]	Photo 6. Backfilling underway
	
Photo 7. Segments installation is in progress[2]	Photo 8. Segments post-tensioning underway[2]

Figure 2.4 Photo essay of elevated guideway construction work

[2] Photos Source: Courtesy of the Canada Line Rapid Transit Inc., Vancouver, British Columbia, Canada.

Photo 9. Work site fencing to ensure safety[3]

Photo 10. Utilities relocation[3]

Photo 11. Asphalt stripping/excavation

Photo 12. Shoring work in level 2[3]

Photo 13. Completed mud cover

Photo 14. SOG fabrication/concrete pouring

Photo 15. Walls & deck slab fab/form/pouring

Photo 16. Backfill laid, leveled & compacted[3]

Figure 2.5 Photo essay of cut and cover tunnel work

[3] Photos Source: Courtesy of the Canada Line Rapid Transit Inc., Vancouver, British Columbia, Canada.

by matching production rates through one or more of scope of work, resource allocation level, or the use of multiple crews (meaning in this context the simultaneous execution of the same work at two or more work locations). Also, work is sufficiently separated in terms of space and time to avoid work site congestion and thus detrimental impacts on productivity. Further, as shown, a good strategy ensures work continuity which ensures efficient resource utilization relating to movable crane operations and balances supply chain management pertaining to off-site activities such as pre-casting. Minimizing the length of the construction foot-print on the work corridor throughout the project duration also contributes to the quality of the schedule, as it helps minimize stakeholder concerns. When time is constrained by contractual requirements, the LP representation helps with determining the minimum number of work faces required.

Figure 2.6 – Schematic linear planning chart- balancing production, achieving work continuity, assessing length of work corridor open.

Figure 2.7 depicts the traditional representation of linear projects via two different bar chart representations: Figure 2.7(a) in which activities are sequenced by start date; and, Figure 2.7(b) in which activities are grouped by location and within a location, ordered by start date. In addition this figure compares as-planned vs. as-built status helping to tell the as-built story.

While the bar chart representations employ visual analytic capabilities relating to comparisons and interactive tools of filtering and zooming, for large-scale linear projects, they do not provide a holistic overview of the schedule, nor do they make easy the task of assessing schedule quality in terms of work continuity, matched production rates, crewing strategy, etc. As observed by Russell and Udaipurwala, 2002, the inherent limitations of bar chart representations stem "from the fact that bar charts essentially provide a local view of the project, i.e. locally within a particular time window, making it extremely difficult to anticipate effects on the global project level for changes made to local activities. Furthermore, for sizeable projects, bar charts can lead to vast, difficult to navigate information spaces in which one can easily lose their bearings". Nevertheless, the strength of the bar chart lies in its long-standing and pervasive use in the construction industry, and the ease with which it communicates work that has to be done and when. Thus, one seeks to complement its strengths, as opposed to seeking a replacement.

An alternative to the use of a bar chart to represent schedule data is a linear planning chart, which positions activities in time and space. As described below, its strengths relate to being able to portray overall schedule strategy in a compact form, and for long linear projects which are the focus herein, it provides valuable insights into the quality of a schedule. Its greatest usefulness is during the planning phase, when overall construction strategy must be determined. In simplified form, this representation can also be useful as a communication tool with various project participants, especially third part stakeholders. While mentioned previously, the real usefulness of the LP representation can only be realized if it is embedded in an interactive modeling environment. This has been done, and relevant details may be found in Russell and Wong 1993, Russell and Udaipurwala 2004, Russell et al. 2006. The focus here is on schedule representation using LP charts, and on how visualization of construction schedule data via linear planning charts helps in assessing quality of a schedule in terms of the metrics described previously, and comparing planned vs. as-built schedules to help identify causes of the non-performance if any, and suggest the most appropriate corrective actions.

Figure 2.8(a) illustrates a holistic view of the case study project schedule in LP form and explains the construction strategy adopted in terms of location sequence to be followed, and how well production rates were balanced, while figure 2.8(b) shows a time and location zoomed segment of the schedule which captures all phase 1 activity locations and several phase 2 activity locations, thereby entrancing clarity and comprehension of the phase wise construction strategy, location work sequence, project scoping, logic relationships amongst the activity planning structures, crewing strategy, and activity production rates.

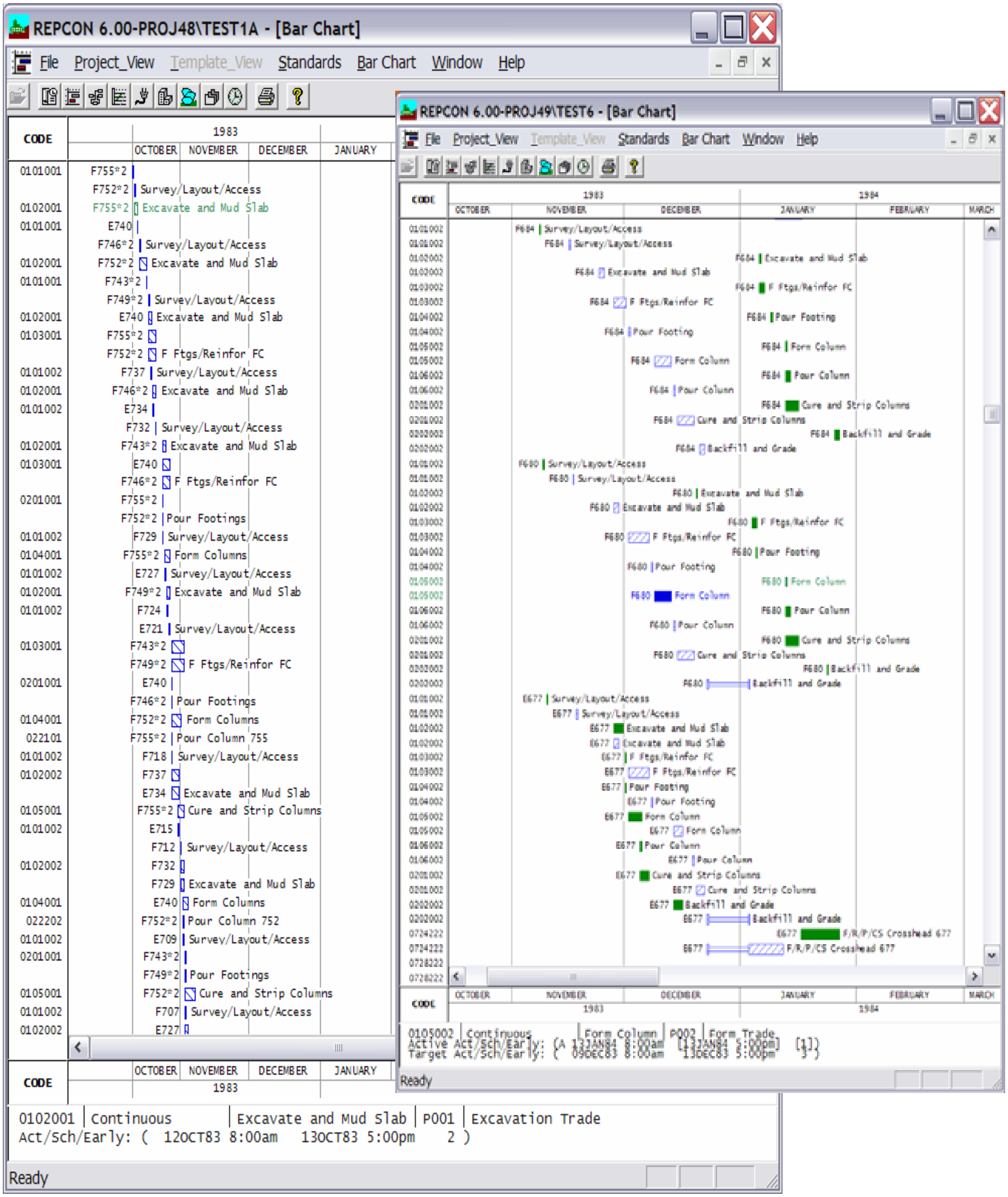


Figure 2.7 (a) Traditional Bar Chart with activities ordered by start date; (b) Activities grouped by location, and comparison bar chart

The intent here is not to critique the original schedule, but rather to show the insights provided by a LP representation. The reader is reminded that the project is modeled as per the approach of 1983 and the then limitations on the modeling tool in terms of capacity and activity types available. Thus, for example, it is broken into 6 sections because of software capacity constraints, and crossheads are modeled using non-repetitive activity structures although such limitations have been rectified in the latest version of REPCON used for modeling this project. If modeled using today's technology, a more elegant representation could be used, allowing greater clarity of the work to be performed. Further, through the power of the associated interactive tools with regards to zooming, content filtering and display options, see figure 2.8(c), combined with the ability to change activity properties and re-compute the schedule, the user is able to conduct an in depth schedule review and optimize the schedule.

In terms of the original schedule, it is observed that there was only one work face (i.e. work started at one end and proceeded in an orderly location sequence to the other end), and production rates for activities of different duration were balanced through the use of crewing strategies (i.e. the simultaneous execution of 2 or more locations of a specific activity). Piling work in the last phase of the project was constrained by resources, leading to an enlarged foot-print of construction activities during the last third of the project. These observations are clearly conveyed through the medium of the LP schedule format. Moreover, the holistic representation of a project through a LP representation provides an opportunity for project participants to check at a glance whether finish milestone requirements if any, are accomplished at any given time. (They were but they are not shown in figure 2.8 – this feature of the software tool was being revised when this thesis work was done). A valuable complement to the LP representation would be direct access to photos of work locations and related components (drawings) to help assess schedule workability, production rates, etc.

As part of the existing interactive interface, the ability exists to tile schedule views, horizontally or vertically. Shown in figure 2.9 in tiled form is a global view of the project schedule in LP form, and a bar chart representation with a more refined level of granularity. In terms of the current implementation, the tiled views are not linked in that as you navigate one, the corresponding activity is not highlighted in the other. The thick bold lines in LP chart and filled bars in bar chart representation show the critical activities. Because of the way the schedule was reconstructed with start milestones to link the phases and no finished milestones with late date constraints, no critical path is shown from beginning to end of the project. It is noted that management and the client are interested in reviewing the critical activities with the view to help the reviewer “to prevent the critical paths from being unreasonable due to intentional and unintentional distortion by inputting inappropriate activities, durations, relationships and time constraints on the paths. Distortion of critical paths may be, while detrimental to the owner, beneficial to the contractor’s future claims on change orders”, (Dzeng et al. 2005).

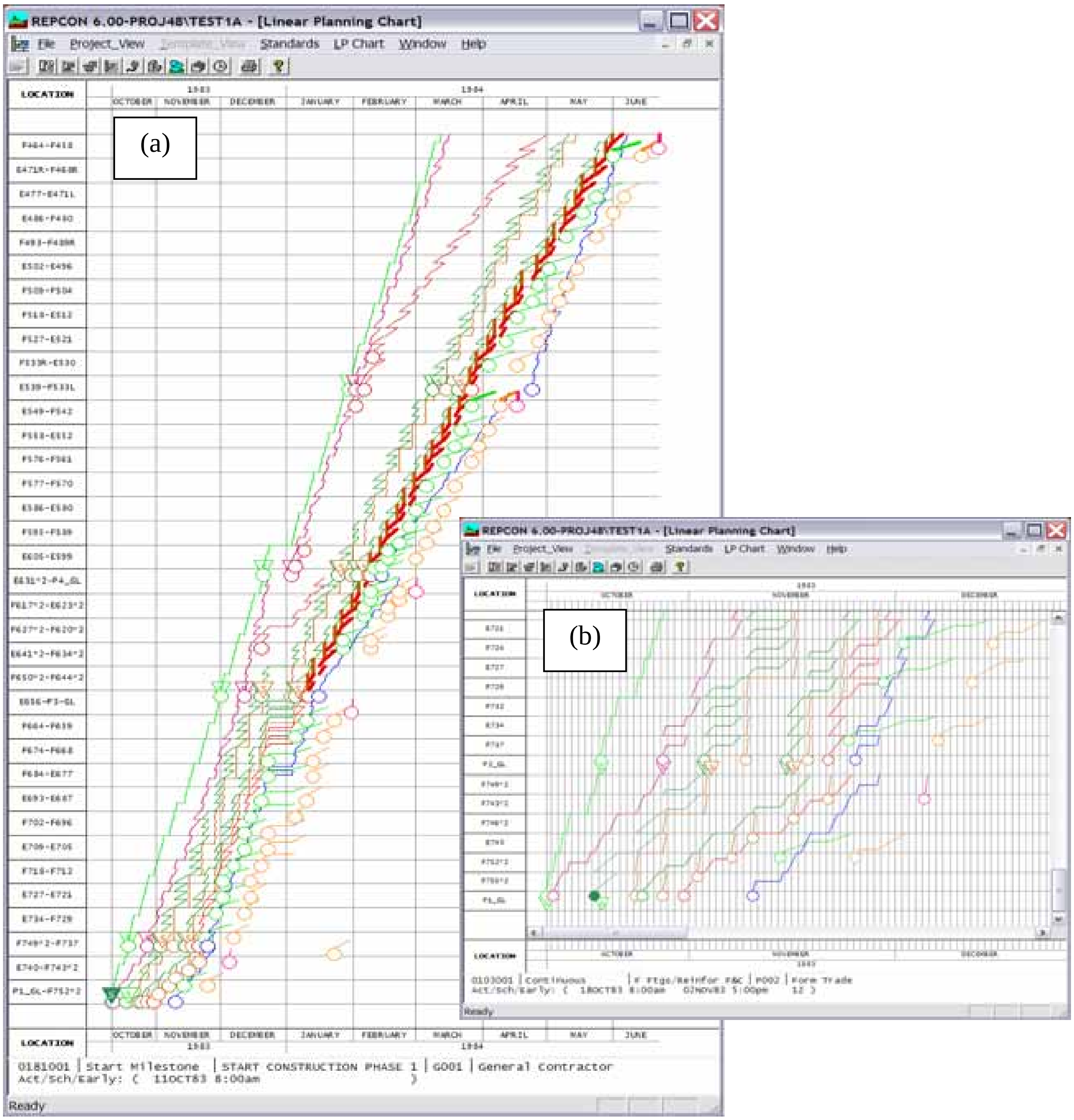
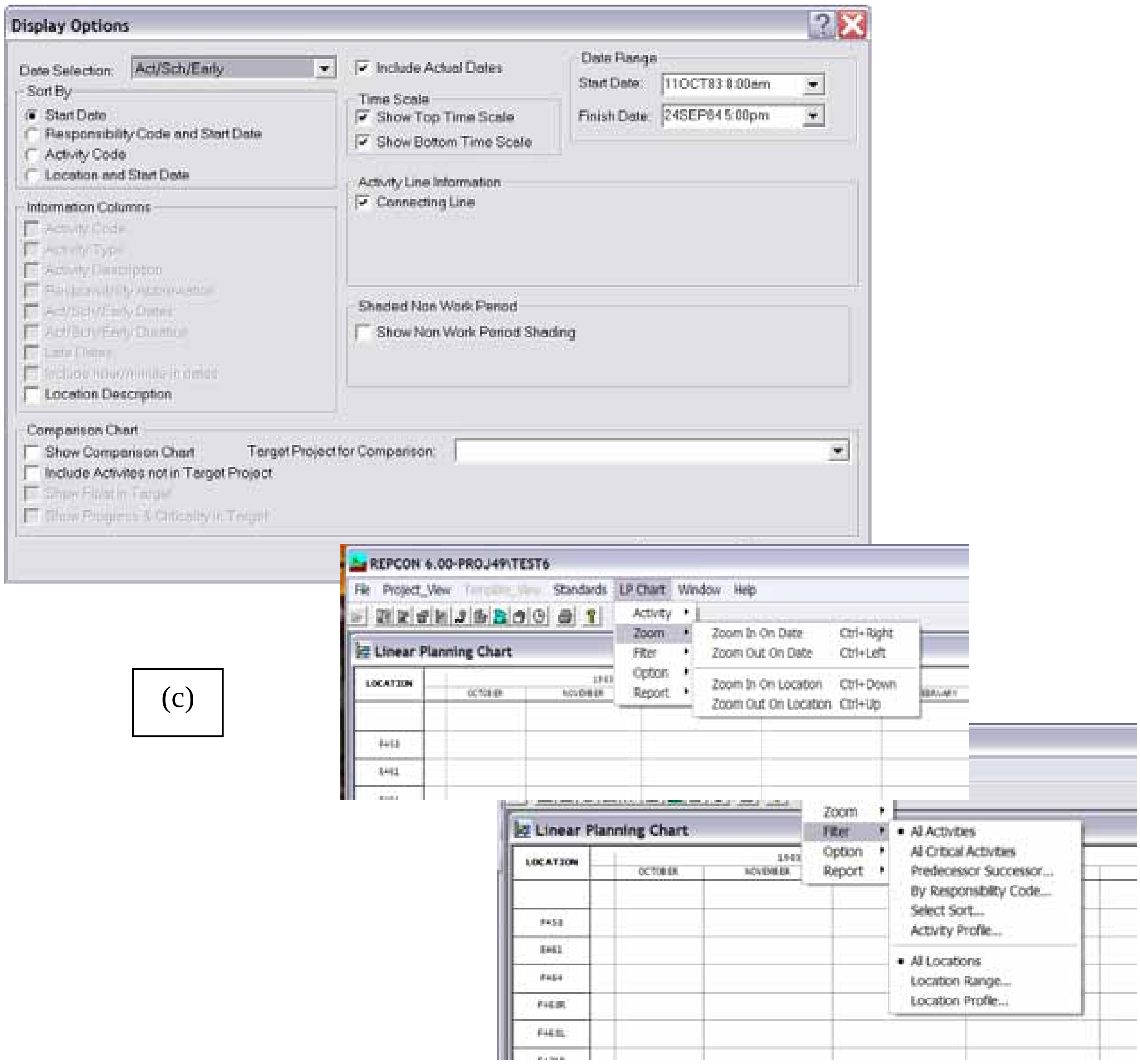


Figure 2.8 (a) As-planned LP chart for 3 km project (global view); (b) zooming in on a narrow time and location window



(c)

Figure 2.8 (c) LP interface human-computer interaction tools (HCI)

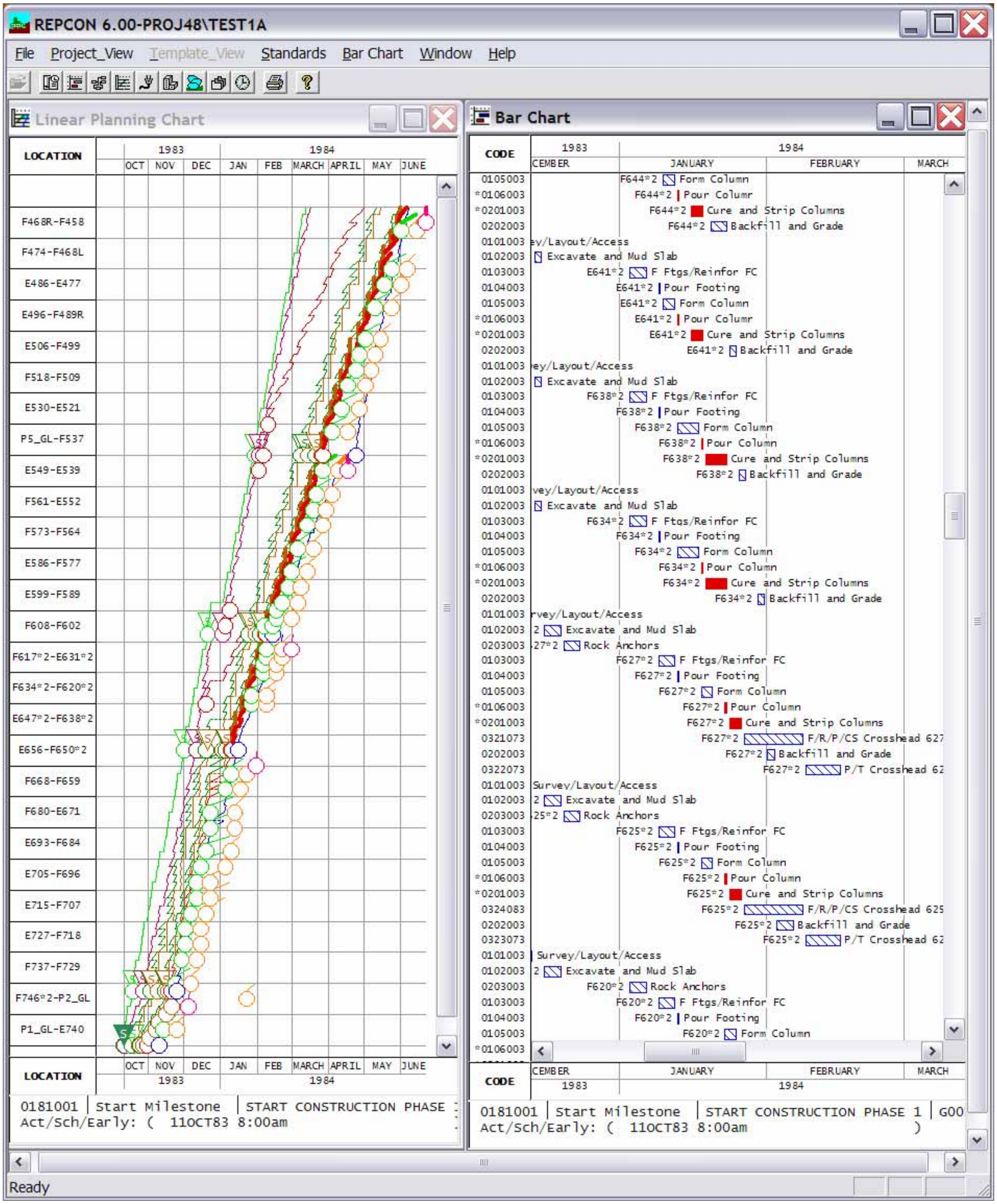


Figure 2.9 Tiling of schedule representations – LP + BC – different granularities of detail

The LP chart schedule representation can also be very useful in telling the as-built story. Depicted in figure 2.10(a) is a schedule representation using actual as opposed to planned dates. As noted from this figure, a significant amount of work was done out of location sequence for the case study project. While the image does not convey reasons for this out of sequence work or delay in completing the project, it does suggest likely productivity losses for the contractor because of the need to shift resources, including crews, formwork, and other equipment, seemingly on a random basis from location to location. The task of the contractor, having portrayed what happened then becomes one of explaining reasons and responsibilities for the pattern of work. Complementing figure 2.10(a) is figure 2.10(b) which provides an overlay of the as-planned vs. as-built schedule of the lead activity excavation and mud slab, over the entire location range and time window to show the trajectory of the work flow. This figure highlights the importance of an interactive environment which allows filtering, color coding and zooming. Filtering allows the user to sieve and visualize activities of interest while color coding emphasizes quick recognition of the planned and as-built data presented. These interactive tools along with zooming in time and space helps in reducing clutter which leads to enhanced clarity of the visualization. “The ability to support extensive filtering and display options is crucial to achieving use in practice”, (Russell and Udaipurwala 2002).

It is noted that a haphazard work sequence, especially in an urban context further complicates the situation through the need for enhanced co-ordination with line agencies for efficient service delivery at multiple locations, traffic management all along the corridor, utility relocation, etc. And while not applicable to the case study project, out of sequence work for an elevated guide way project can be devastating due to the fact that construction of a pre-cast segmental guideway beam makes use of a traveling truss (see figure 2.4) that needs to move in an orderly location sequence. Otherwise the attendant efficiencies are lost because of the need to dismantle, transport and reassemble the truss on a repeated basis.

Review of the as-built schedule in LP chart format while the project is underway provides important insights to management pertaining to the identification of the quanta of problems that caused the work to be performed out of sequence, and can assist management and client in taking prompt remedial actions to get the project back on track.

2.6.2 REPRESENTING AND INTERPRETING THE AS-BUILT STORY (OBJECTIVES 2 AND 3)

Examined in this sub-section are several images that help convey the as-built story of the project along with possible reasons for the performance achieved. Unlike the LP scheduling graphic, interaction with the graphic by users is limited to zooming, highlighting, brushing, and manipulating the colors used.

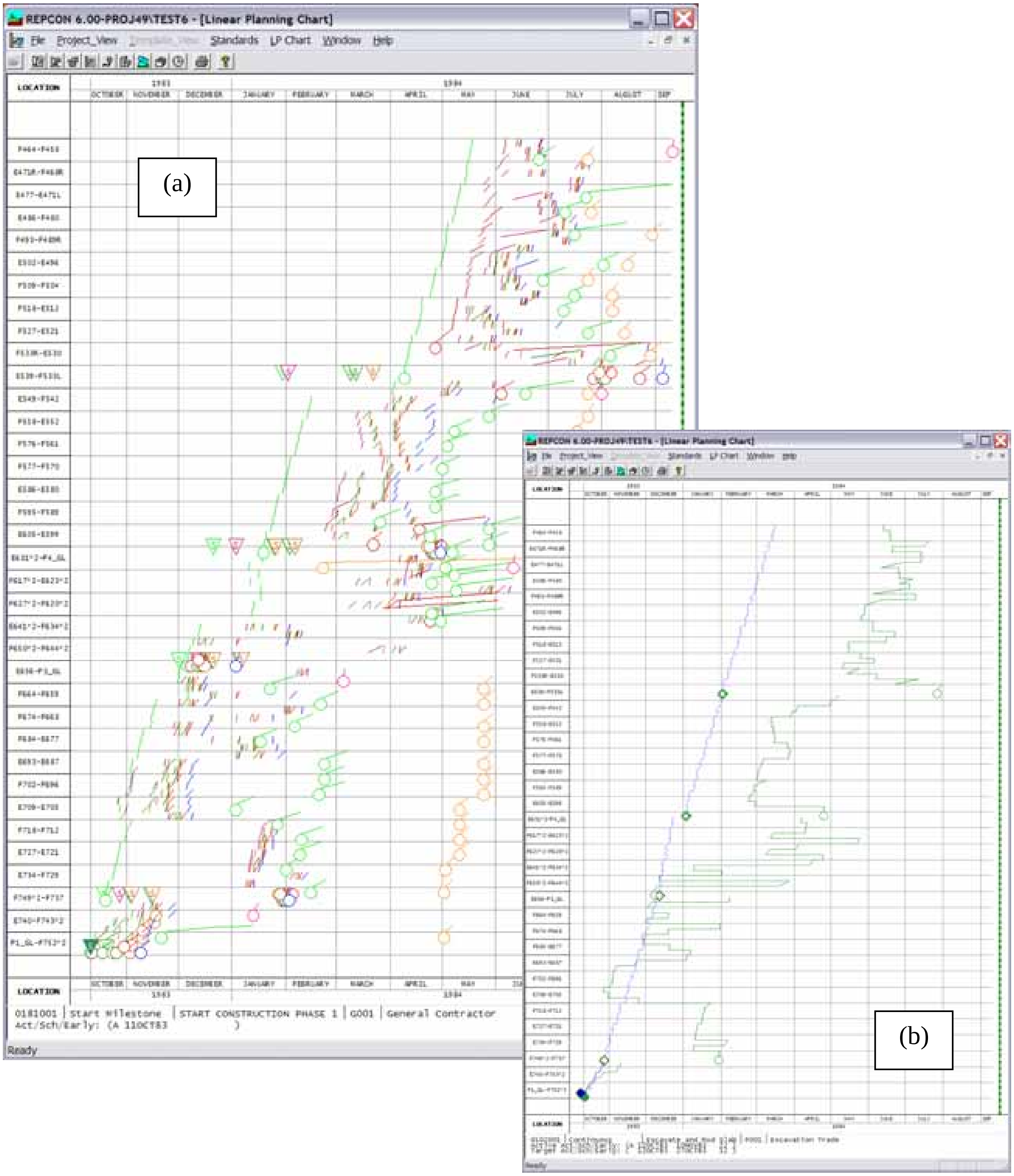


Figure 2.10 (a) As-built LP chart – provides insight on the extent of out-of-location sequence work performed; (b) comparison LP chart for lead activity, excavation & mud slab – showing planned vs. actual work trajectory;

Displayed in figure 2.11 is a comparison of the as-planned vs. as-built production rate for two phases of the excavate and mud slab activity. A number of messages can be deducted from such an image, including (a) the planned production rate was achieved or bettered in the majority of the cases; (b) exceptions to expected performance are clearly discernable; and, (c) clustering and or trends of superior or inferior performance can be readily determined. The clarity of the image allows the user to pinpoint specific locations for further investigation in order to identify reasons for performance below expectations. As currently implemented, the interface does not allow ready navigation through other activities. What is supported, however is the ability to zoom, assisting with project scale, the ability to show the same activity twice so that overview and detail can be explored, (which means that one image provides a holistic view of the data while the other provides the detailed/local view to gain more clarity), and the ability to manipulate color. The ability to superimpose this graphics on the linear planning chart would add considerable value to the user.

Figure 2.12 depicts the 15 categories of problem codes used to classify individual problems that occurred in the field and their properties including time lost, mhrs lost, and responsibility, if any, for the event. The list of the problems appearing under each category reflects both an attempt over several years to standardize problem codes as well as a significant number of additions to reflect the relatively fine-grained description used by the contractor in compiling the project history. Given the previously described challenges associated with linear projects in an urban environment, a significant number of problems may be encountered including multiple instances of a particular problem, and, it is very important to document problems encountered in order to identify trends early on. Although it is easy and tempting to create a fine grained division of problems which can lead to a proliferation of problem codes, such a division can creates difficulties for discerning patterns. Nevertheless, that was what was done by the contractor, and we have simply replicated the detailed breakdown. From a system designer perspective, it would be useful to include a feature to permit the aggregation of the consequences of individual problem codes up to the category level, and then for data analysis and visualization purposes, work at the category level. This has not been done, but should be considered as part of future work. It would help with gaining more insight from problem visualization.

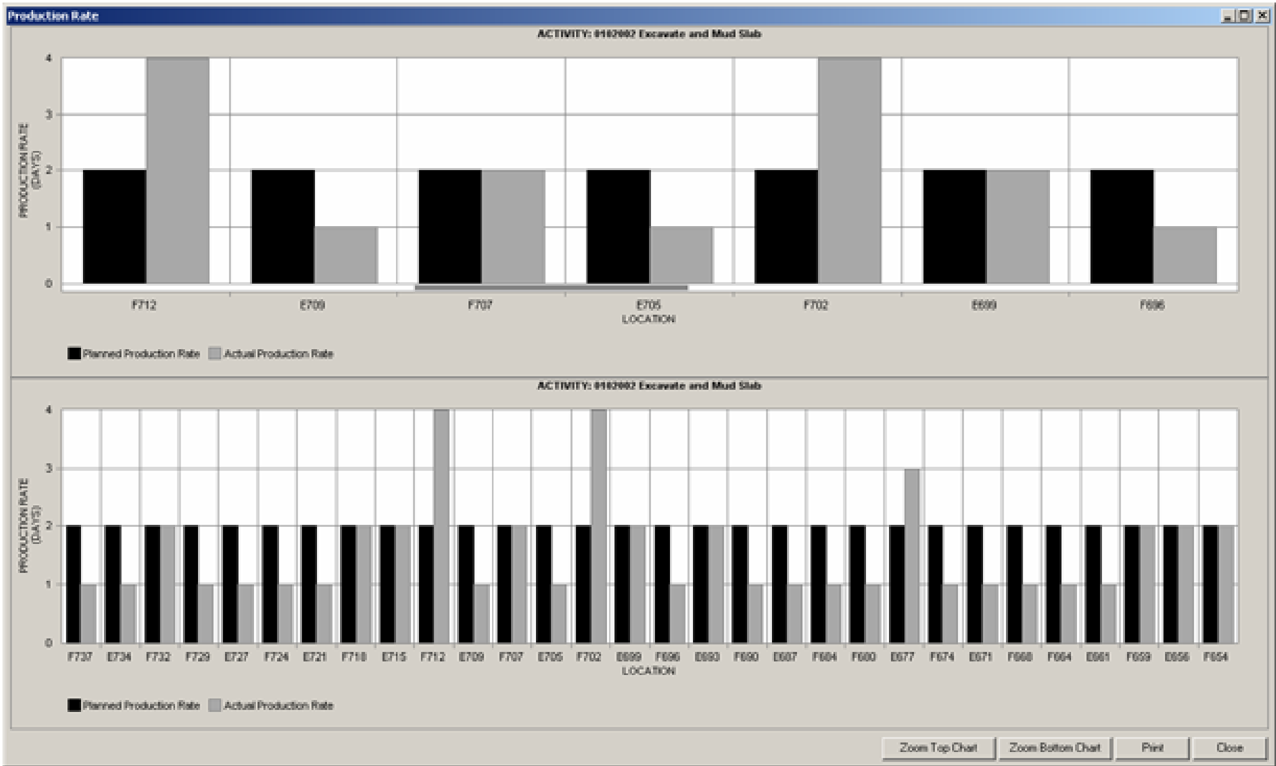


Figure 2.11 - Planned vs. actual production rates of excavation & mud slab activities

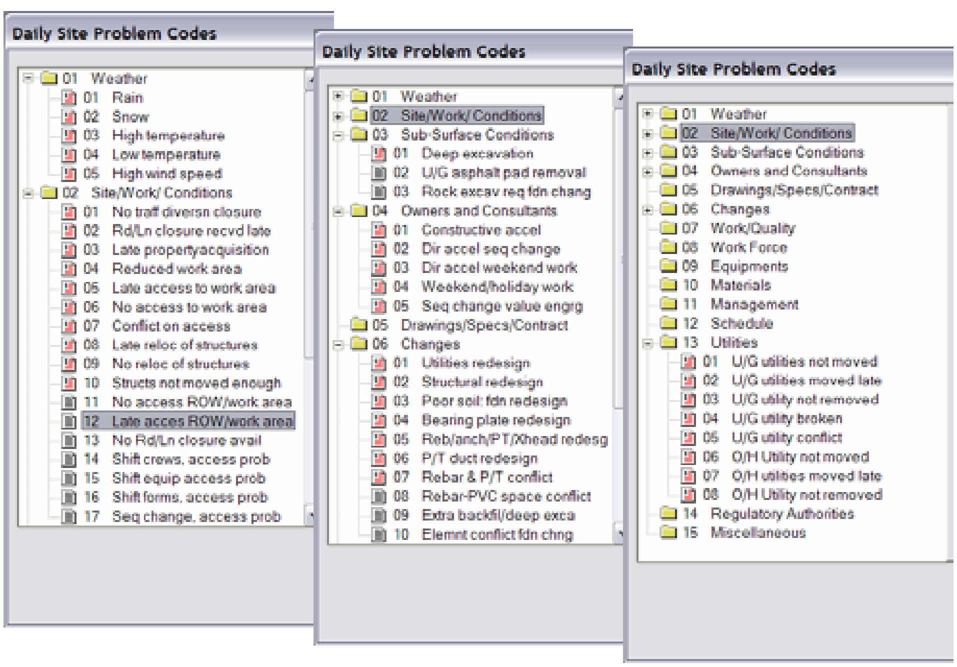


Figure 2.12 Problem codes for capturing the story

Figure 2.13(a) shows the interface used for recording information at the project level (e.g. site environment level) and activity by activity on a daily basis. As described previously, as part of the work described herein, temperature, precipitation and wind data is entered. Such data is important to correlate with instances where performance difficulties were said to occur because of one or more weather factors. The planned and as-built daily status of activities are symbolized as “s”, “o”, “f”, and “d” and “S”, “O”, “F”, “P”, and “D”, respectively to represent start, ongoing, finish, postponed and same day started and finished.

Problems encountered during execution of the project, compiled and documented by the project’s contractor’s perspective, are categorized and coded using the schema shown in figure 2.12 and associated with individual activities as shown in figure 2.13(b). The exclamation “!” against the actual daily status of an activity indicates that one or more problems were associated with the activity on that day. Overlay of figures 2.13(a) and (b), through linked data views, would help in identifying the type(s) and number(s) of problem(s) associated with a specific day.

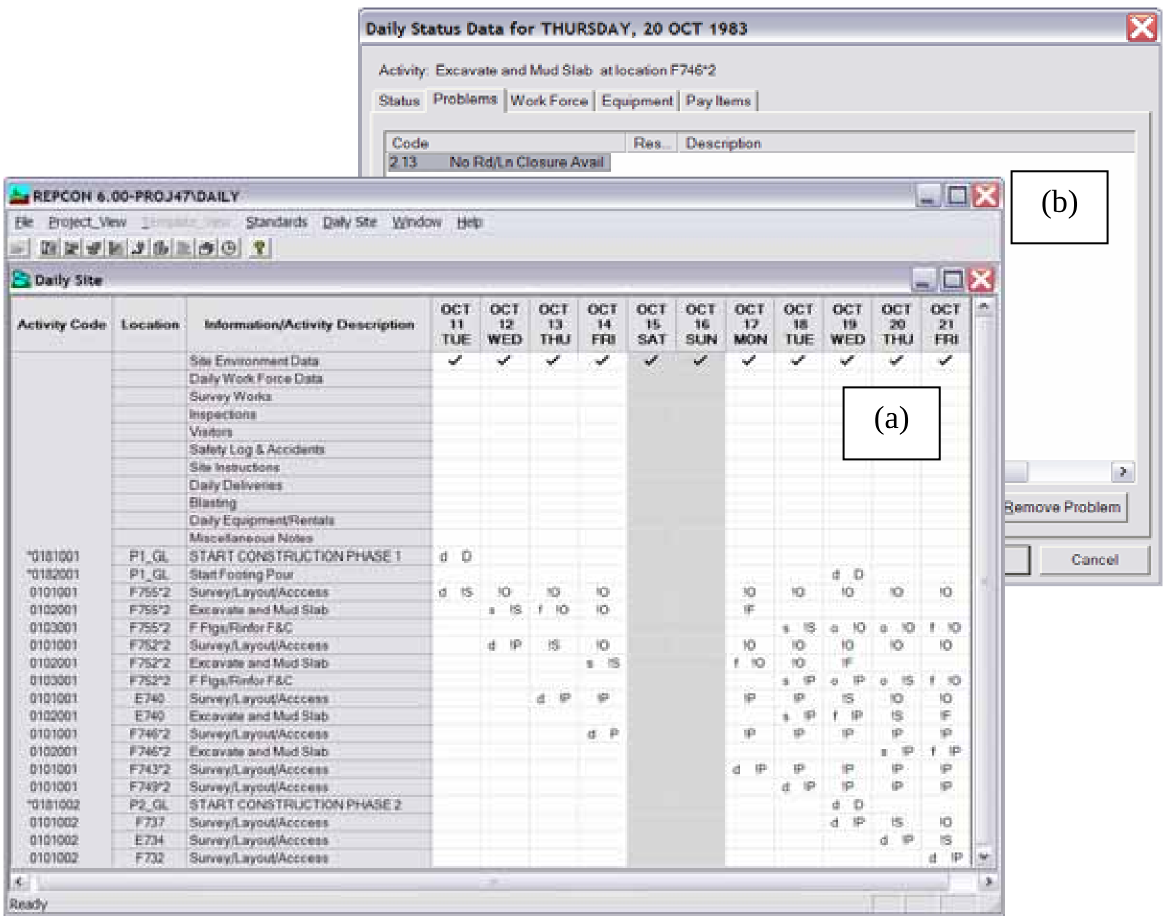


Figure 2.13 – (a) Recording daily status; (b) recording problems

Figure 2.14 provides an overview of aspects of the natural environment in which the project was executed. Up to 3 graphs per image can be selected (shown) and available choices include sky condition, precipitation, temperature, wind speed, ground conditions and access to site. It is possible to select the same item twice, allowing one to show an overview of the visual structure while the other graph provides a magnified focus of one area, on the same image using the zoom feature. The value of the figure lies in its ability to portray a large amount of data in a compact form, which can help in identifying patterns/clusters which reflect abnormal environmental site conditions which in turn could help explain time delays and productivity losses. This is explored further in figure 2.16. The REPCON system, if augmented with the ability to combine figure 2.14 with as-built linear planning chart and bar chart graphics could assist construction personnel to develop a more holistic understanding of project performance.

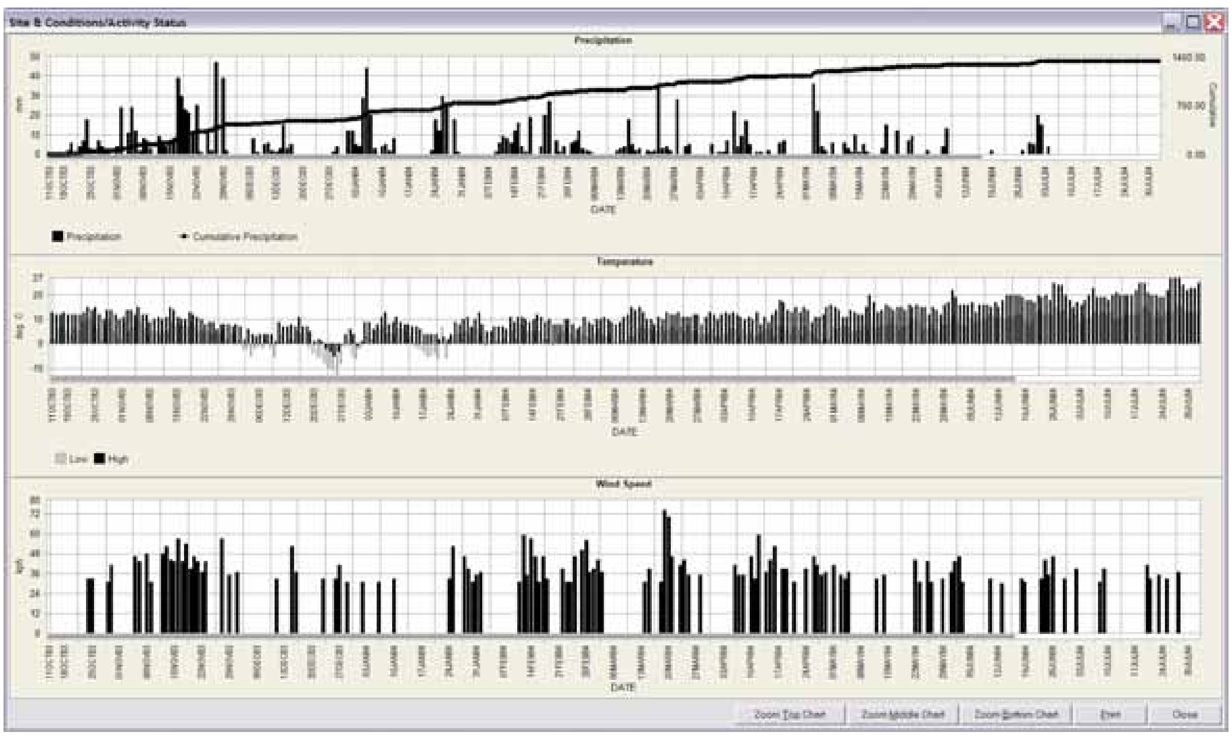


Figure 2.14 – Representing the natural environment in which project is constructed

Figure 2.15 portrays an overview of all of the problems encountered in terms of the number of occurrences, (each daily occurrence of a problem is counted). It is important to note how this figure was generated. First, the graph was generated for all problem codes. Items with a zero count were then noted, and a problem code profile for item with a non-zero count created. Thus, a problem code profile was used to generate figure 2.15. Creating such chart could be eased through employing a one step procedure which incorporates a sub-routine in the REPCON system to consider only those problem codes that have non-zero counts.

The ability to generate the figure provides instant feedback to management at any point during the project's execution, helping management to direct its attention to the most problematic areas. As shown in the figure, problem count has been used as the performance metric. Other choices include time lost and man-hours lost. Data for these two choices was not available. In terms of enhancing the graphic, it is observed that only five problems categories were in play: 2 site/work conditions; 3 sub-surface conditions; 4 owners and consultants; 6 changes; and, 13 utilities. It would be useful to show the hierarchy, or allow for an overview + detail image, the overview giving performance by category, the detail giving the breakdown within a highlighted category. Incorporation of such a feature is left to future research work.

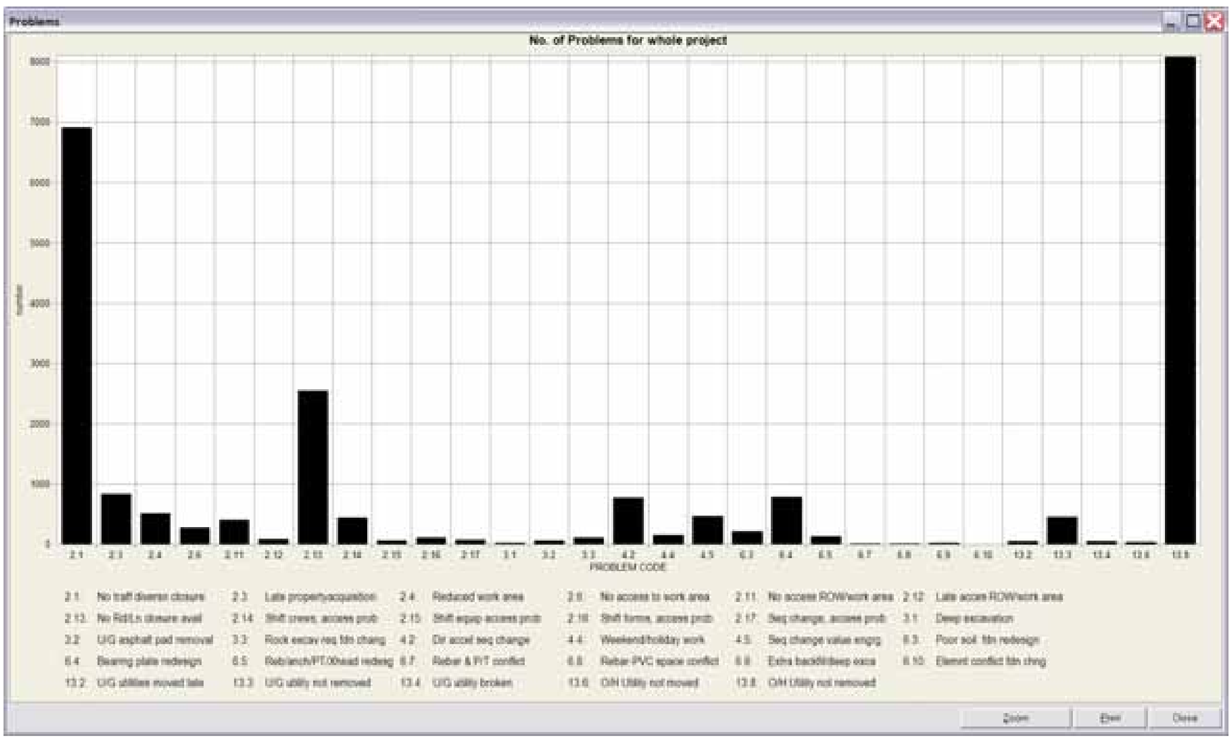


Figure 2.15 – Distribution of problems by type – all activities, locations and project start to finish from contractor perspective

Figure 2.16 represents an extension of figure 2.14. Daily and cumulative precipitation over a time window and maximum and minimum daily temperatures are shown in part (a) and (b) respectively while part(c) depicts the daily status for the activity of interest at a specific work location. The ability to juxtapose environmental site condition with activity status can help construction personnel explain reasons for performance for activities that are sensitive to abnormal environmental site conditions, thus providing insight on cause and effect relationships. Improvements to this image could include the ability to interlink the three views so that they scroll simultaneously and the ability to point at a specific daily activity status and receive a listing of problems encountered and consequences.

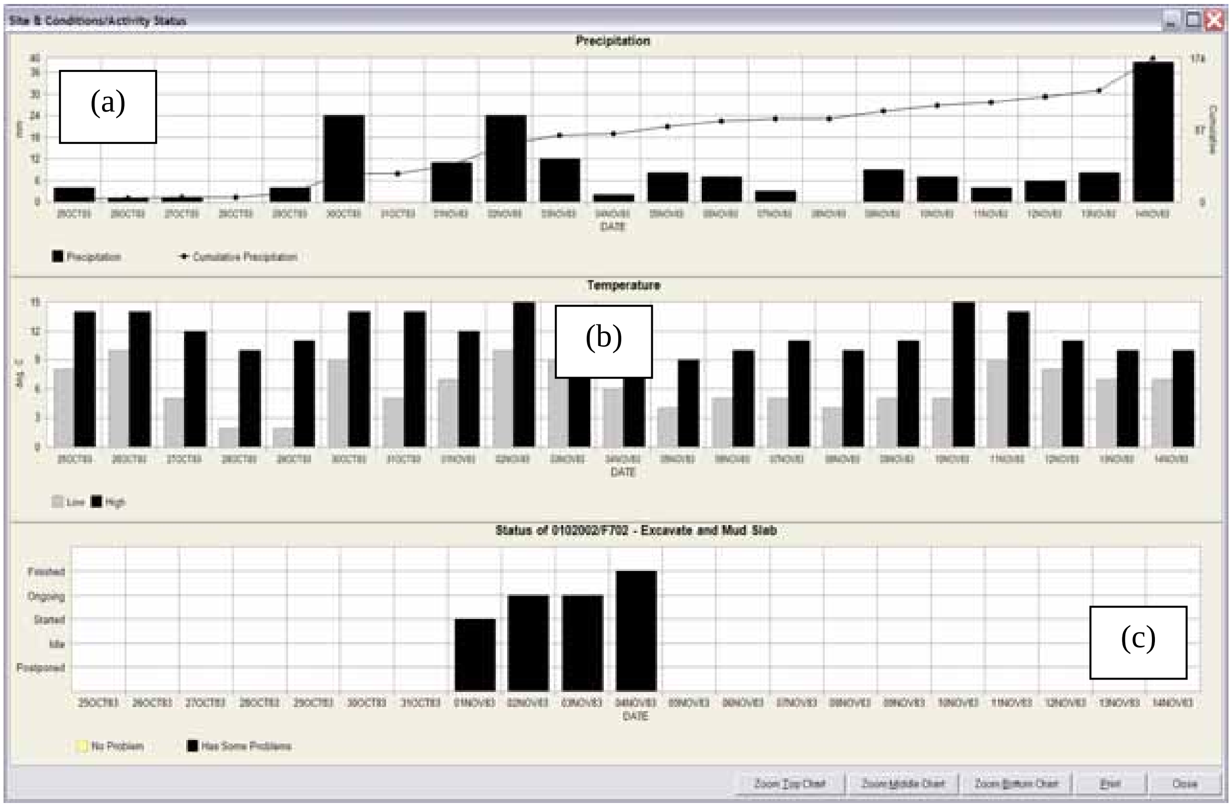


Figure 2.16 (a, b, c) – juxtaposition of site conditions and activity status - excavation and mud slab for location 702

Figure 2.17 is a 3 dimensional (3D) plot representing date on x-axis, activity status on y-axis and locations on z-axis with the view to comprehend the daily status of an activity (in this case Excavate and Mud slab for Phase 2) in time and by location to identify status/problem clusters or trends in time and space. It provides important and instant feedback to the reviewer/management on the probable causes of delays, duration of a specific activity on a location by location basis and patterns of problem encountered. To enhance comprehension, the activity status bars are color coded to indicate particular problem encountered. An unresolved difficulty is how best to treat status when multiple problems are recorded for same day. The ability exists to rotate and zoom the image to narrow focus and enhance understanding, thus furnishing a direct idea about the factors/problems responsible for delays of the work at hand, in this case excavation and mud slab activities at various locations. Figure 2.17(b) underscores the importance of the interactive view transformation tool “brushing”, which allows the user to highlight activity status on a specific date and location to enhance clarity while removing the surrounding “clutter”.

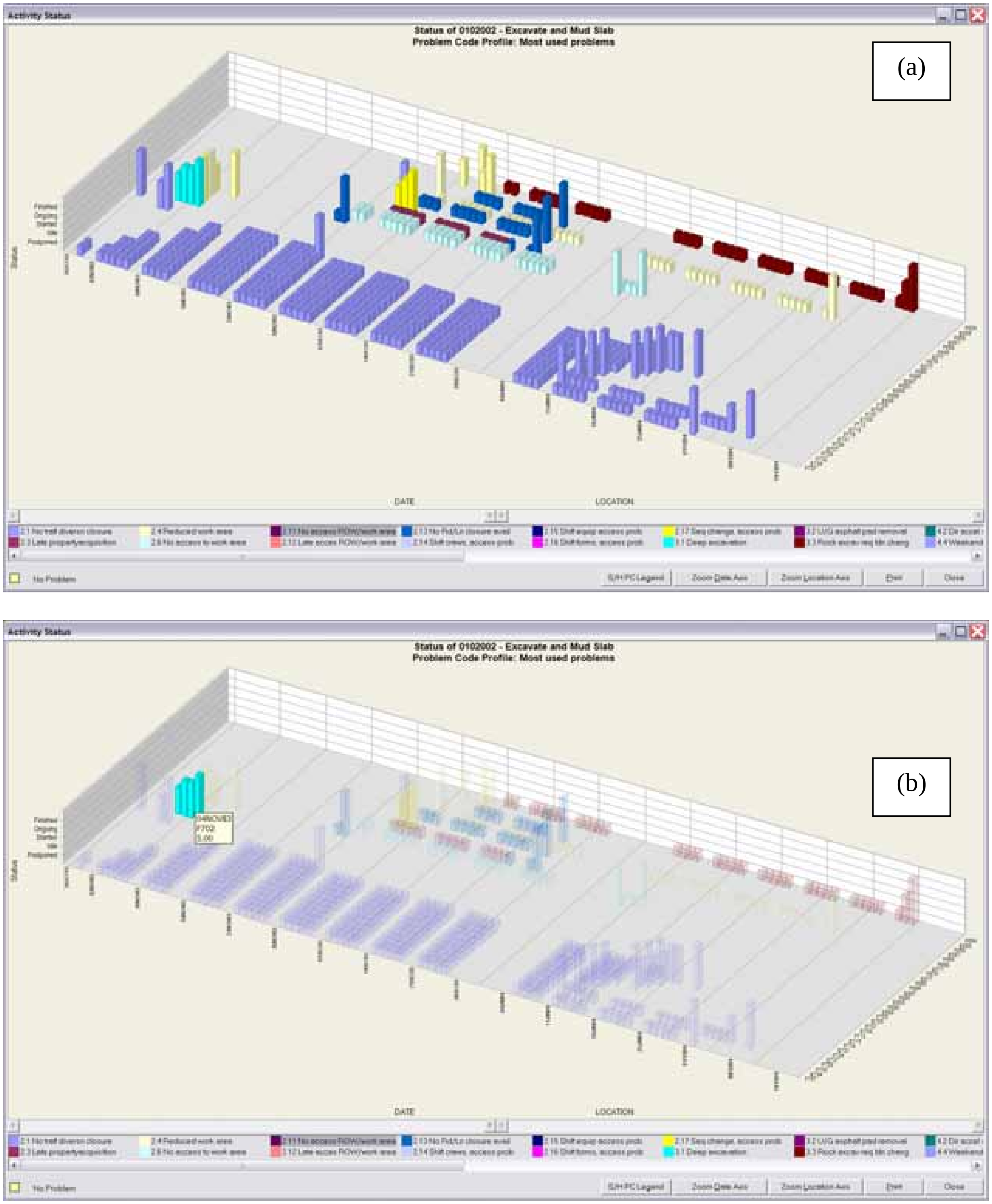


Figure 2.17(a) Activity status by date, location; (b) Use of brushing to point out specific problem code

Figure 2.18 provides a global view of all problems encountered on a day-by-day basis for all activities with the goal being to identify the clustering of problems. This image represents in an effective and very compact form, a 4000 to 5000 page report that identifies all problems recorded. Moreover, such a large data sets of problems could also be displayed using tree and tree map representation to show hierarchies. It is virtually impossible to create a mental image of problem distribution that corresponds to the visual image in figure 2.18 by browsing the tabular report. This observation speaks to the power of data visualization as well as the challenge of comprehending the large volume of data that accompanies projects of significant size. The ability exists to generate this image for any arbitrary activity profile, problem code profile, and time window. Brushing is also supported, allowing the user to readily highlight a date and problem code of interest. However, the ability to explore different profiles on the fly is not supported. To change profiles, the user has to close the current image, re-specify content profiles, and then recreate the image. This is a limitation of the software utility used. Another feature that would be useful would be to allow for the aggregation of problems by problem category.

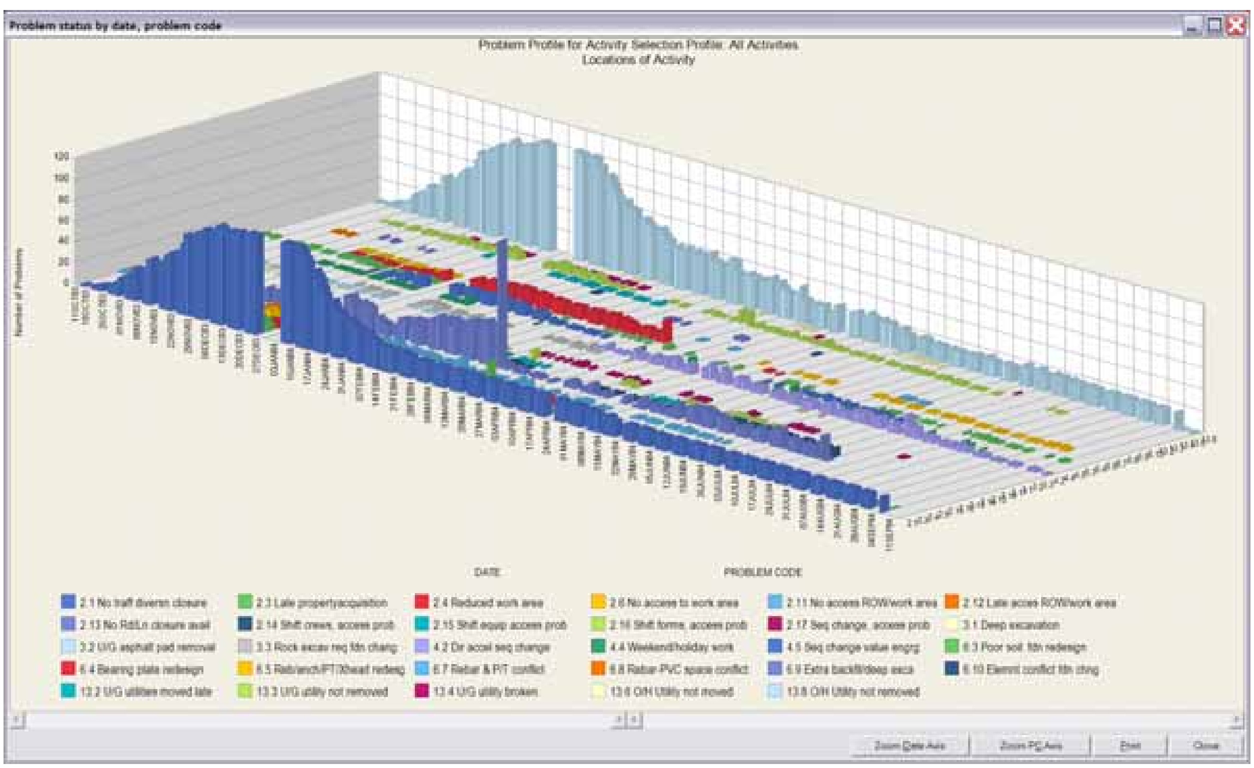


Figure 2.18 Problem status by date and problem code

Figure 2.19 shows the distribution of the number of occurrences of problems vs. locations, thus representing a global view of the problems in terms of location range while assisting management in exploring reasons for productivity loss and or delays at locations of interest. Again this image can be generated for user specified activity and problem code profiles, as well as for user specified date and location ranges. It has the virtue of condensing a very significant amount of information into a compact image, thereby providing insights on clustering of problems by type and location. As before, it would be useful to support the aggregation of problems by problem code category.

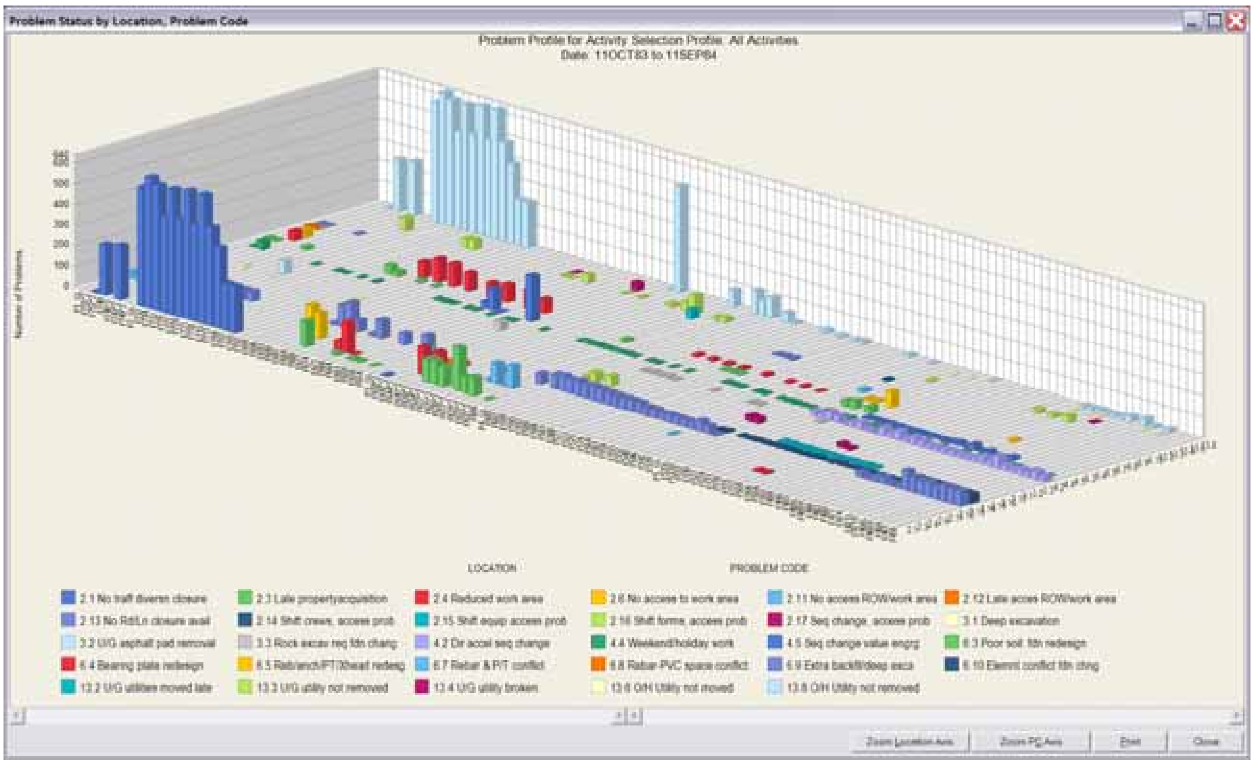


Figure 2.19 Problem status by problem code and location

Figure 2.20 represents distribution of a single problem profile (number of occurrences) on a daily basis for a user specified activity profile (in this case, the excavation and mud slab activity for all project phases, thereby covering all project locations). The image helps management to focus on individual instances and clustering of a single/specific problem in time and by location and facilitates communication with the relevant agency responsible for addressing the problem, in this case providing lane or road closure to allow execution of the work. Color coding has been used to distinguish between locations, and by being able to rotate the figure, the resulting work pattern is shown.

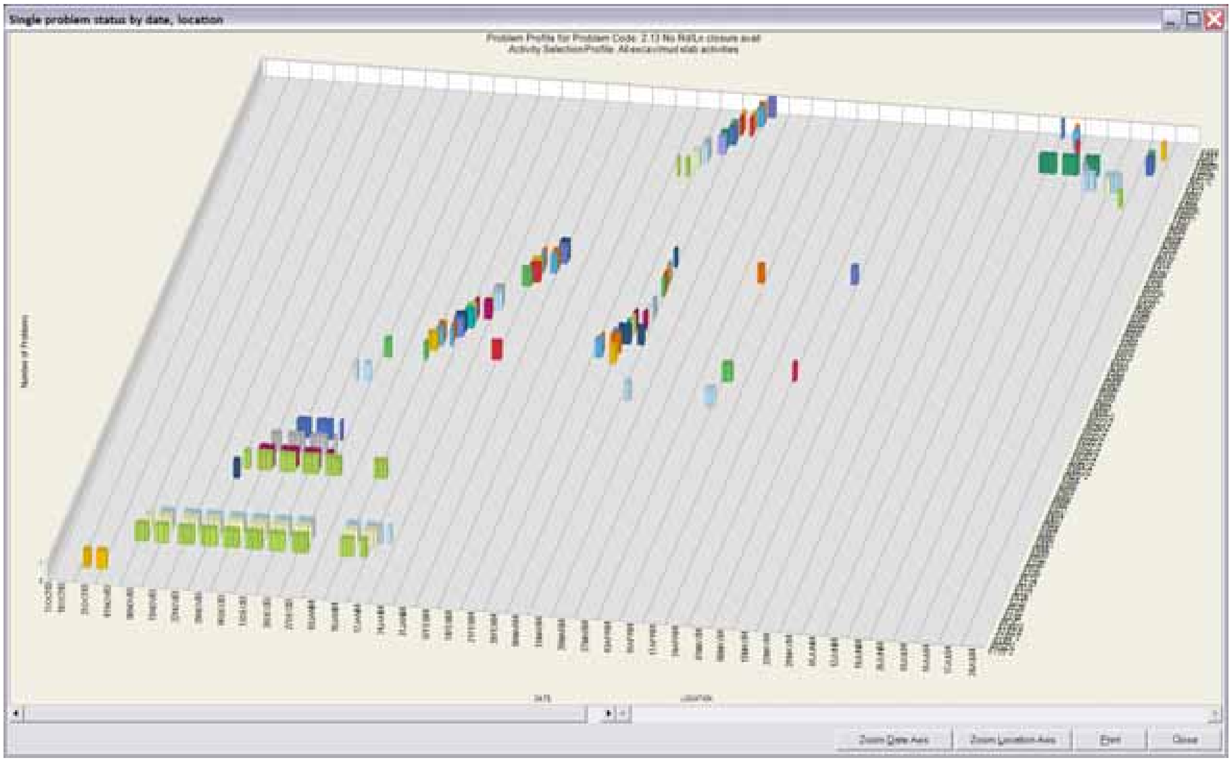


Figure 2.20 Single problem status by date and location

2.7 IMAGES CRITIQUE AND SUGGESTIONS FOR IMPROVEMENT (OBJECTIVE 4)

In this section, a critique of the various images presented in the previous section is given, with emphasis on those in section 2.6.2. Observations are summarized in tabular form.

The system used to generate visual insights is the REPCON system, which houses the entire project data used. REPCON makes use of its own customized schedule graphics routines plus ChartFX 6.2 Client Server, for as-built graphics. ChartFX provides a platform for its users to conveniently integrate charting into their applications with minimal development. It has built-in intuitive menus, dialogues and toolbars thus providing the end-user with chart customization capabilities. The provision of its enhanced human computer interface enables users to change the charts to a variety of formats through the chart gallery tool bars. It can also help the user to store changes to a particular chart for future sessions, maximizing the usability and readability of the application’s charts at the end-user level.

The use of the REPCON system to visually analyze construction data involves querying data from the REPCON database through the REPCON’s graphic user interface (GUI) widgets. The dimensions of data that can be queried are predefined and dependent on the choices of visual encoding. For example, if only one view and positions on three orthogonal axes and color hue in that view are chosen to encode data, the number of dimensions of data we can query is four. However, if more than one view is placed in the visualization substrate (superimposed or juxtaposed), the number of dimensions of data we can query increases. A default configuration of visual encoding (e.g.: 2D bar chart, 2D scatter plot, 3D colored bar chart, juxtaposing several charts, etc.) is predefined by subroutines that load queried data and call certain graphics function provided by ChartFX in order to generate visual representations of the queried data. For example, shown in figure 2.21 is the dialogue box for querying site condition and activity status data, and then instructing the system to visualize data for figure 2.16 in the previous section.

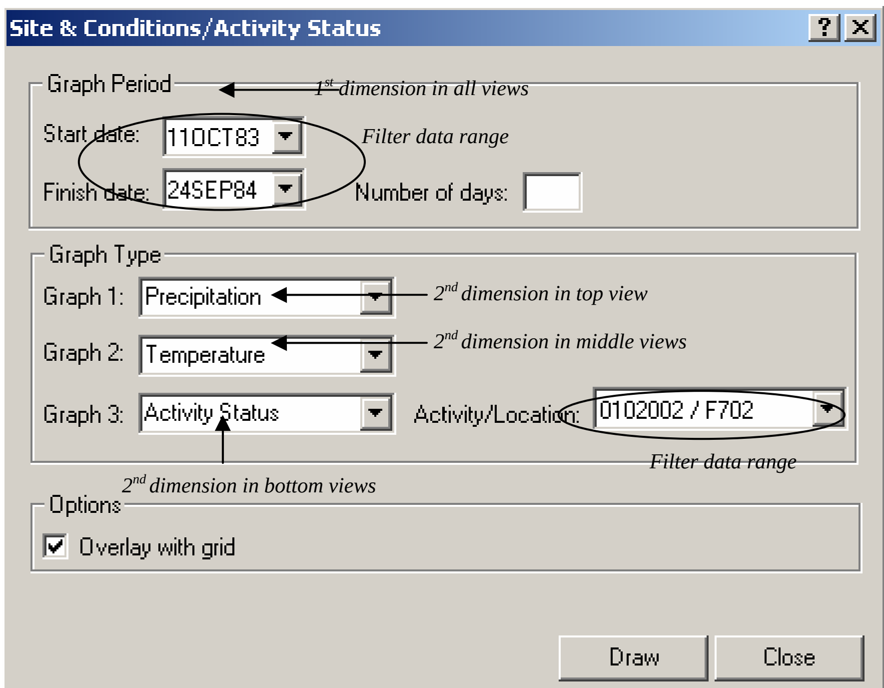


Figure 2.21 Dialogue box in REPCON for querying data

In analyzing the images generated by the REPCON system, consideration needs to be given to visual encoding (VE), human computer interaction (HCI), and overall purpose (Task). Visual encodings relate to the mapping of queried data into visual representations that are sensory to humans, and can be discussed under the headings of choice of visual marks, choice of properties of visual marks, and choice of layout of visual marks. Human-computer interaction relates to the ability to perform direct manipulation on a visual representation or through the use of GUI gadgets for intuitively querying the data (visual query), and for reading a visual representation on user demand (view transformation). Once the default visualization is generated using ChartFX for the data queried in figure 2.21, the platform provides a human computer interaction (HCI) environment for exploring the views of visualization as shown in figure 2.22. The most important features of HCI environment supported by the ChartFX chart platform are as followings:

1. View transformation by changing choice of visual marks which is done by changing types of charts from the chart gallery as shown in the top chart, changing colors of visual marks, depicted in the middle chart and changing the use of 2D space or 3D space is presented in the bottom chart of the figure 2.22;

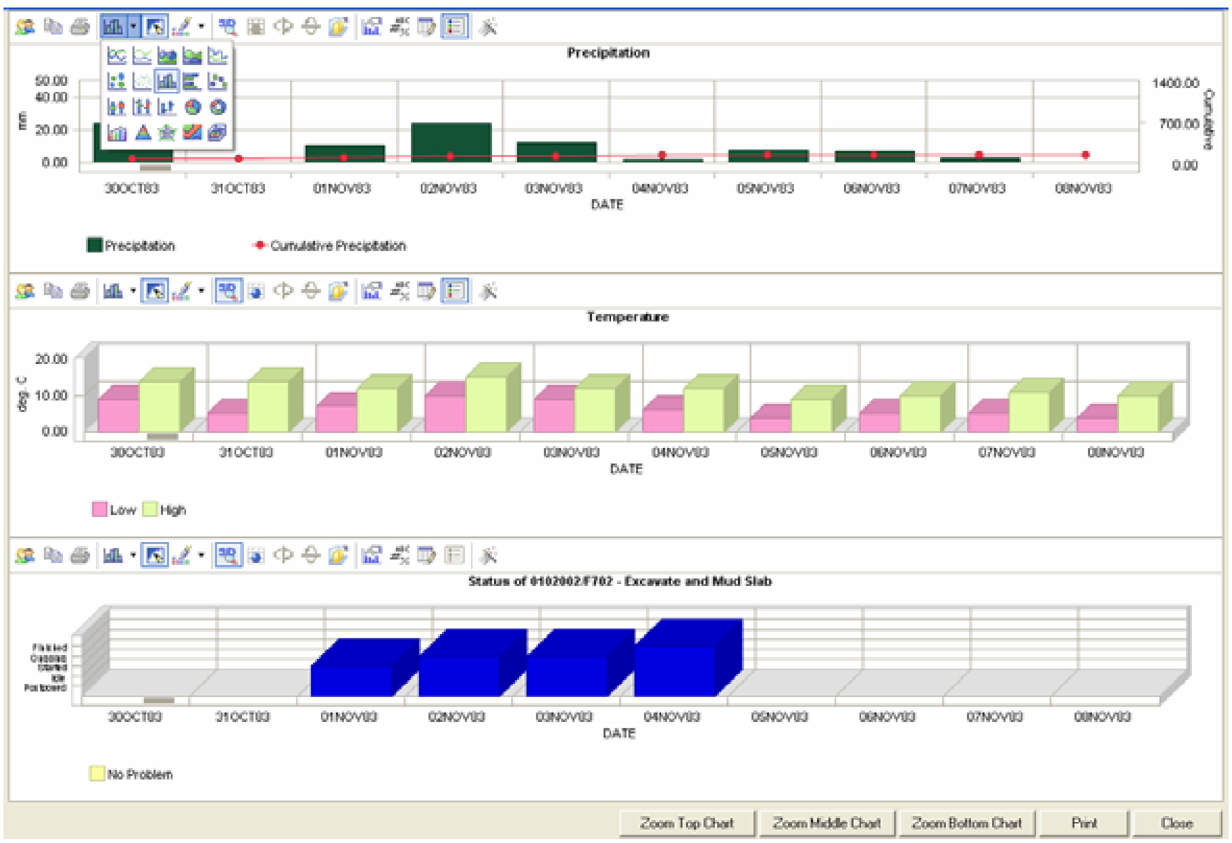


Figure 2.22 ChartFX supported human computer interaction (HCI) - view transformations by changing choice of visual marks.

2. View transformation by two way labeling (brushing on textual label causes only the data corresponding to that label to be visualized and vice versa) and conditioning by brushing. Both functionalities are presented in figure 2.23, where brushing enables two ways labeling of the data with top information box in the visualization and the highlighted legend-label in the context of the representation. Moreover, as reflected in the figure 2.23, the conditioning

refers to the highlighting of a single visual mark (one bar) or a series of bars of the data to gain more clarity and comprehension.

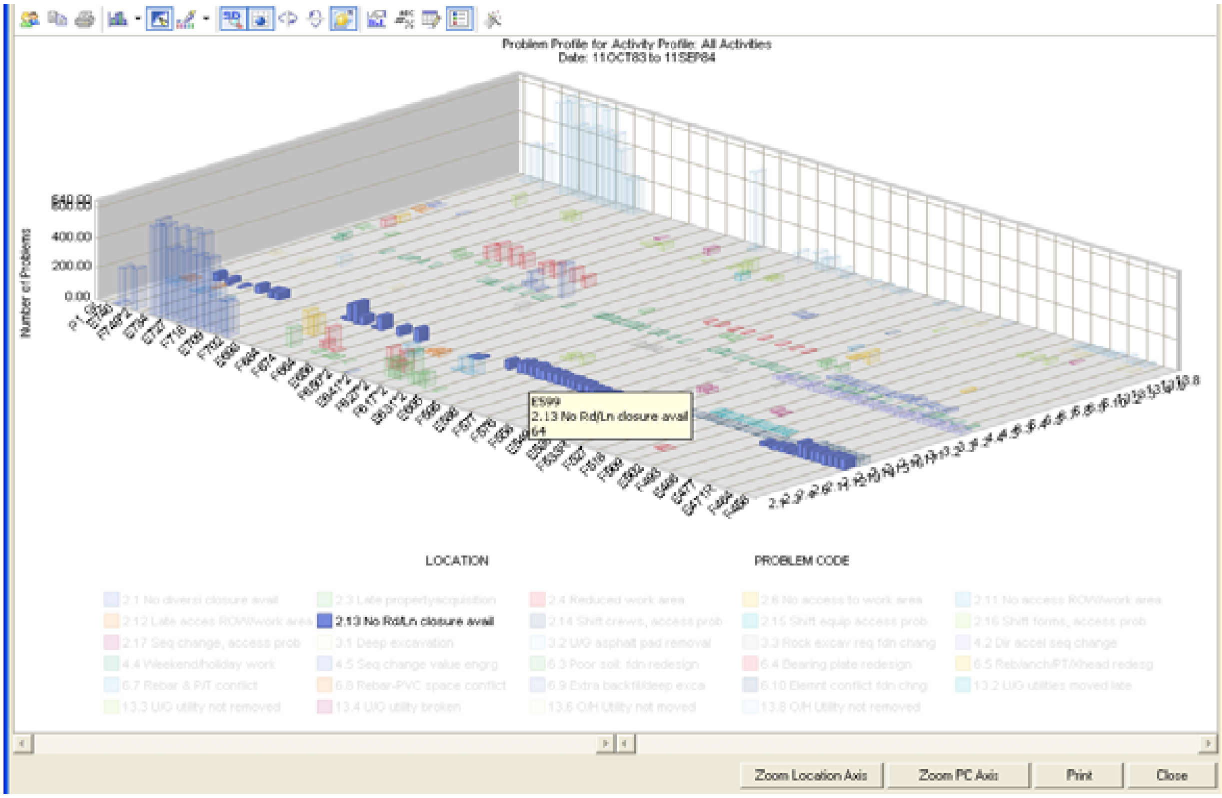


Figure 2.23 ChartFX supported human computer interaction (HCI) - view transformations by two ways labeling and conditioning.

3. View transformation by navigating through the views by zooming in/out and rotating axes. Figure 2.24 shows these view transformations in terms of portraying a holistic view of problems encountered via zooming in space/locations and rotating axes to present a global view of the problems encountered during project execution. Palette color coding as well as axes rotation which is being controlled through the pointer on the globe is presented in the properties dialogue box in figure 2.24.

   The overall purpose of visual images deals with the tasks involved in acquiring information in terms of facts reading and detecting interesting patterns. It is the last two of these that are treated in a somewhat simplified fashion and examined in the context of the images presented. The focus of the analysis is on the disparities between HCI features in the REPCON system and intended information tasks. Where disparities are identified, solutions by using state-of-the-art visualization techniques are proposed. Analysis of the images generated by the REPCON system (Figures 2.7 to Figure 2.11; and Figures 2.14 to Figure

2.20) in terms of their purpose, visualization features used, and critiques, is summarized in Table 2.1.

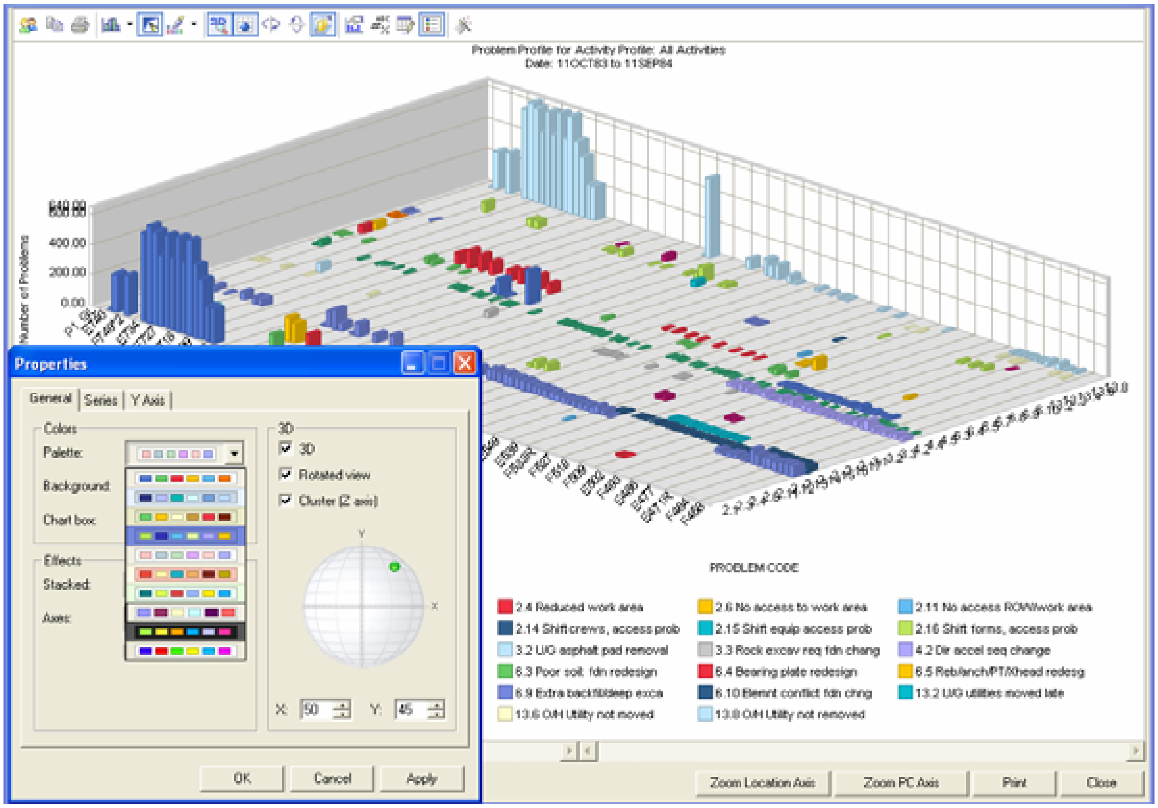


Figure 2.24 ChartFX supported human computer interaction (HCI) - view transformations through navigating the views in/out and rotating axes.

Figure	Image type	Purpose	Features	Critique	Technique used
Figure 2.7 – Bar chart	2D bar charts representing temporal data	1. To identify when specific activities are to be carried out; content can be organized/grouped a number of ways – by start date, by location, by project participant 2. To compare production rates of an activity to be executed on different locations.	**Filters** – activity profile, time window, location window **Color** – use to differentiate between critical and non-critical activities, planned vs. actual **Zooming** – can zoom in/out on time **Overlays** – planned vs. actual	**Strengths:** It is well understood and a traditional way of communicating a schedule **Weaknesses:** It is very difficult to develop a holistic understanding of a schedule – lack of compactness. Need to link with other data within same image (e.g. photos, environmental data)	Visual encoding formalism; Interaction techniques for data transformation; View point control; Overlay
Figure 2.8 – LP chart – (a)overview & (b) details	2D linear planning charts representing temporal data	1. To identify when, where and by whom specific activities are to be carried out. 2. To compare production rates of an activity to be executed on different locations, and show the location work sequence. 3. To assist with assessing schedule quality in terms of matching production rates, opportunities for work continuity, identifying areas of work congestion	**Filters**- activity profile, time window, location window, project participant **Color**- use to differentiate work of project participants **Zooming**-can zoom in/out on time and location	**Strengths:** 1. Better choices of visual encodings for linear project process data make LP chart much more compact than traditional bar chart. 2. Easy to identify the location sequences for executing linear projects and assess schedule quality **Weaknesses:** Activity labeling problem; loses power where minimal repetition of work occurs between locations. Need to link with other data within same image (e.g. photos, environmental data)	Visual encoding formalism; Interaction techniques for data transformation; View point control;

Figure	Image type	Purpose	Features	Critique	Technique used
Figure 2.9 – Tiling with different schedule representations	2D linear planning chart and 2D bar chart (horizontally juxtaposed) representing temporal information	1. Allows simultaneous examination of complete schedule and investigation of details using same representation on both sides scaled differently, or two different representations, as shown.	**Filters**- no additional filters than the individual **Color**- no additional use than the individual **Zooming**- no additional use than the individual **Overlays –** planned vs. actual	**Strengths:** 1. Allows governing details to be identified and impact on overall schedule to be assessed. **Weakness:** 1. Views are not linked, so activity navigation in one not matched with simultaneous navigation in the other. Need to link with other data within same image (e.g. photos, environmental data)	Visual encoding formalism; Interaction techniques for data transformation; View point control; Overlay
Figure 2.10 – LP As-built and comparison	(a) 2D linear planning chart and (b) 2D linear planning chart superimposed representing temporal data	1. To identify when specific activities were carried out. 2. To compare production rates of an activity executed on different locations. 3. To know the location sequences of actual activity execution. 4. To compare production rates and location sequences of as-planned activity executions and as-built activity execution	**Filters**- no additional filters than the individual **Color**- if overlay as-built on as-planned, only use two colors to differentiate them **Zooming**- no additional use than the individual **Overlays –** planned vs. actual	**Strengths:** 1. Clear graphic of actual pattern of work, and comparison of planned vs. actual path or work and production rates. 2. Better choices of visual encodings for linear project process data make LP chart much more compact than traditional bar chart. **Weaknesses:** Activity labeling problem. Need to link with other data within same image (e.g. photos, environmental data)	Visual encoding formalism; Interaction techniques for data transformation; View point control; Overlay

Figure	Image type	Purpose	Features	Critique	Technique used
Figure 2.11 Comparison – planned vs. actual property of an information entity	Two 2D bar charts *(vertically juxtaposed)* for representing multi-dimensional information	1. To compare as-planned and as-built activity duration on different locations – a similar graph exists for productivity by transforming data for product and process views	**Filters**- activity, as-planned or as-built **Color**- use to differentiate as-planned and as-built **Zooming**- can zoom in/out on location **Brushing**- condition as-planned or as-built data to be presented **Overlays**- planned vs. actual	**Strengths:** 1. Helps identify patterns/clusters of performance 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-the-art HCI techniques for constructing, placing, and linking different views of relational data.	Visual encoding formalism; Overview + detail; Interaction techniques for data transformation; View point control; Location probes
Figure 2.14 Natural environment	Three 2D bar charts *(vertically juxtaposed)* for representing multi-dimensional information	1. To understand how weather, ground and site conditions are distributed in time 2. To identify anomalous conditions 3. To identify whether there are certain condition patterns clustering in certain time windows	**Filters**-time window, weather, ground, site conditions **Color**-can be used, adds minimal value **Zooming**- can zoom in/out on time **Brushing**- condition data to be presented **Overlays –** indirectly through stacked graphs	**Strengths:** 1. Provides insights on clustering/patterns of various project conditions 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-art HCI techniques for constructing, placing, and linking different views of relational data.	Visual encoding formalism; Interaction techniques for data transformation; View point control; Overlay; Location probes

Figure	Image type	Purpose	Features	Critique	Technique used
Figure 2.15 Problem counts – overview graphic	2D bar chart for representing multi-dimensional information	1. To understand the distribution of problems encountered in terms of the number of occurrences (daily existence means one count of occurrence), or consequences of problems encountered in terms of time or mhrs lost	**Filters**- time window, problem profile, responsibility, problem count, time lost, mhrs lost **Color**- can be used, adds minimal value **Zooming**- can zoom in/out on problem profile **Brushing**- condition problem to be presented	**Strengths:** 1. Provides overview of distribution of problems or their consequences 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-the-art HCI techniques for constructing, placing, and linking different views of relational data.	Visual encoding formalism; Interaction techniques for data transformation; View point control; Location probes
Figure 2.16 Juxtaposition of site conditions and activity status to search for causal relationship as a function of work type	Three 2D bar charts *(vertically juxtaposed)* for representing multi-dimensional information	1.To understand how the weather condition and a certain activity status distributed in the time window 2.To identify whether there is a link or causal relation between weather /site condition and activity status	**Filters**- time window, weather / site condition factors, activity/location **Color**- used to differentiate between problem/non-problem days **Zooming**- can zoom in/out on time **Brushing**- condition data to be presented	**Strengths:** 1. Helps to identify possible causal relationships between project conditions and activity performance 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-the-art HCI techniques for constructing, placing, and linking different views of relational data.	Visual encoding formalism; Interaction techniques for data transformation; View point control; Location probes

Figure	Image type	Purpose	Features	Critique	Technique used
Figure 2.17 – (a)Activity status by date and location; (b) illustration of use of brushing	Three 2D bar charts *(vertically juxtaposed)* for representing multi-dimensional information	1. To understand the daily status of an activity in time and location 2. To understand the association between activity status and problems, and identify status/problem clusters or trends in time and space	**Filters**- time window, location profile, activity, problem profile **Color**- use to differentiate problems **Zooming**- can zoom in/out on time and location **Brushing**- condition location to be presented	**Strengths:** 1. Provides insights into activity status, problems encountered in time/space – their clustering and distribution 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-the-art HCI techniques for constructing, placing, and linking different views of relational data.	Visual encoding formalism; Interaction techniques for data transformation; View point control; Location probes
Figure 2.18 Problem status by date and problem code	3D bar chart for representing multi-dimensional information	1. To understand how the number of problem occurrences is distributed in time window for a certain problem (similar graphs possible for time and mhrs lost). 2. To understand how the number of problem occurrences are distributed for a given problem code profile on a certain date 3. To identify clustering/trends of problem occurrences by type and time.	**Filters**- time window, location profile, activity profile, problem profile **Color**- used to differentiate problems **Zooming**- can zoom in/out on time and problem **Brushing**- condition problem to be presented	**Strengths:** 1. Provides insights on distribution of problems by type and time 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-the-art HCI techniques for constructing, placing, and linking different views of relational data.	Visual encoding formalism; Interaction techniques for data transformation; View point control; Location probes

Figure	Image type	Purpose	Features	Critique	Technique used
Figure 2.19 Problem status by problem code and location	3D bar chart for representing multi-dimensional information	1. To understand the distribution of problem occurrences by location for a specified time window and activity profile 2. To provide insights on clustering of problems by type and location	**Filters**- time window, location profile, activity profile, problem profile **Color**- used to differentiate problems **Zooming**- can zoom in/out on location and problem **Brushing**- condition problem to be presented	**Strengths:** 1. Provides profile of problems encountered on a location by location basis 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-the-art HCI techniques for constructing, placing, and linking different views of relational data	Visual encoding formalism; Interaction techniques for data transformation; View point control; Location probes
Figure 2.20 Single problem status by date and location	One 3D bar chart for representing multi-dimensional information	1. To understand how the number of occurrences of a problem are distributed in a time window at a certain location (similar graph for time lost and mhrs lost). 2. Can provide insights on reason for actual location sequence if problem is of type go/no-go – e.g. access	**Filters**- time window, location profile, activity profile, problem **Color**- used to differentiate location **Zooming**- can zoom in/out on location and date **Brushing**- condition location to be presented	**Strengths:** 1. Provides insights on influence of go/no-go problem on actual work sequence for specified activities 2. Well understood and a traditional way of visualizing abstract data. 3. Adequate use of color in visualization **Weaknesses:** Lack of state-of-the-art HCI techniques for constructing, placing, and linking different views of relational data	Visual encoding formalism; Interaction techniques for data transformation; View point control; Location probes

Table 2.3 Analysis of images in terms of image type, purpose, features, critique and technique used.

2.8 CONCLUSIONS AND FUTURE RESEARCH WORK

The construction industry is confronted with challenges related to handling and representing multi-dimensional, multi-source and time varying data in support of management functions relating to planning, organizing, directing/leading and controlling for the project phases of pre-construction, execution, and post-project analysis. Demonstrated in this thesis is the ability to visualize heterogeneous construction data in an effective and efficient manner employing visual analytic and interactive techniques. A key virtue of the images examined is the ability to represent in compact form vast volumes of data in a way that assist management to gain insights and improve decision making and communication amongst project participants. Specifically, it was concluded that the ability to portray schedule data in a linear planning chart as well as other schedule representations combined with pictorial representations of the construction corridor and methods to be used, when embedded in an interactive environment can assist greatly with the task of assessing the quality of construction schedule/plans in terms of the construction strategy as well as capturing as-built story of the control phase of the project execution while addressing issues of scalability and complexity of data.

Further, it was demonstrated that data visualization is a powerful paradigm in capturing and telling a project's as-built story from various perspectives, including working conditions encountered and distribution of problems in time and space. Finally, by critiquing the various images presented, it has been concluded these images have numerous strengths, there is a need to improve its human computer interactive capabilities, and in particular, to take advantage of the latest state-of-the-art technologies.

Future work will be directed at designing visual images for a broader range of construction data and management functions (e.g. as-built data in the form of change orders, request for information (RFI's), photos, etc.), at enhancing the human computer interaction components (e.g., highlight and overlay, linked data views), exploiting latest state-of-the-art tools for data visualization (such as future versions of ChartFX), and creating composite images with linked views (such as linking bar and LP chart and their association with photos and environmental data), in order to explore the benefits of a more holistic visualization environment.

2.9 REFERENCES

Ahlberg, C. and Shneiderman, B. 1994. Visual information seeking: Tight coupling of dynamic query filters and start-field displays. Proceedings of CHI, ACM Press Boston, pp. 313-317.

Baskinger, M. and Nam, K. C. 2006. Visual narratives: the essential role of imagination in the visualization process. ACM International Conference Proceeding Series Vol. 243. Proceedings of the Asia Pacific Symposium on Information Visualization. Vol. 6, pp. 217-220

Beermann, D., Munzner, T., and Humphreys, G. 2005. Scalable, robust visualization of very large trees. Proceeding of EuroVis 2005, IEEE VGTC Symposium on Visualization, pp. 1-8.

Bertin, J. 1983. Semiology of graphics. Madison, WI: University of Wisconsin Press.

Card, S. K., Mackinlay, J. D., and Shneiderman, B. 1999. Readings in information visualization: Using vision to think. Morgan Kaufmann Series in Interactive Technologies, Morgan Kaufmann publisher.

Chiu, C., and Russell, A. D. 2007. Construction process data plus visualization tools equals performance insights. ASCE Construction Research Congress, Academic Event Planners, LLC, USA.

Dzeng, R. J.; Tserng, H. P.; and Wang, W. C. 2005. Automating schedule review for expressway construction. Journal of Construction Engineering and Management, Volume 131, Issue No. 1, pp. 127-136.

El-Rayes, K. 2001. Object-oriented model for repetitive construction scheduling. Journal of Construction Engineering and Management, Vol. 127, No. 3, pp. 199-205.

El-Rayes, K. and Moselhi. O. 1998. Resource-driven scheduling for repetitive activities. Construction Management and Economics, Vol. 16, No. 4, pp. 433-446(14).

Environment Canada Web Site for past environmental/weather data http://www.climate.weatheroffice.ec.gc.ca/advanceSearch/searchHistoricDataStations

Hegazy, T., Elhakeem, A., and Elbeltagi, E. 2004. Distributed scheduling model for infrastructure networks. Journal of Construction Engineering and Management. Vol. 130, Issue No. 2, pp. 160-167.

Hyari, K. and El-Rayes. K. 2006. Optimal planning and scheduling for repetitive construction projects. Journal of Management in Engineering, Vol. 22, No. 1, pp. 11-19.

Keim, D. A. 1996. Databases and visualization. Proceedings of the ACM SIGMOD International Conference on Management of data, Montreal, Quebec, Canada.

Korde, T., Wang, Y., and Russell, A. D. 2005. Visualization of construction data. 6th Construction Specialty Conference, Toronto, Ontario, Canada. CT-148-1 to CT-148-11.

Liston, K., Fischer, M., and Kunz, J. 2000. Designing and evaluating visualization techniques for construction planning. Computing in Civil and Building Engineering, pp. 1293-1300.

Nielsen, Y. and Erdogan, B. 2007. Level of visualization support for project communication in the Turkish construction industry: A quality function deployment approach. Canadian Journal of Civil Engineering. 34: pp. 19-36.

Norman, D. A. 1993. Things that make us smart. Defending human attributes in the age of the machine. Perseus Books, New York.

Pilgrim, M., Bouchlaghem, D., Loveday, D., and Holmes, M. 2000. Abstract data visualization in the built environment. Proceedings of IEEE International Conference on Information Visualization, London, pp. 126-134.

Qin, Q., Zhou, C., and Pie, T. 2003. Taxonomy of visualization techniques and systems – Concerns between users and developers are different. The State Key Lab of Resources and Environmental Information System, Institute of Geographic Science and Resources Research, Chinese Academy of Sciences, Beijing, China.

Russell, A. D. and Udaipurwala, A. 2000. Assessing the quality of a construction schedule. Proc., of the ASCE Construction Congress VI, Orlando, Florida, USA, 928-937.

Russell, A. D. and Udaipurwala, A. 2002. Construction schedule visualization. Proceedings of the International Workshop on Information Technology in Civil Engineering, Washington D. C., USA, pp. 167-178.

Russell, A. D. and Udaipurwala, A. 2004. Using multiple views to model construction. CIB World Building Congress, Toronto, Canada. 11 pages.

Russell, A. D. and Wong, W. C. M. 1993. A new generation of planning structures, Journal of Construction Engineering and Management, ASCE, Vol. 119, Issue No. 2, pp. 196-214.

Russell, A. D., Udaipurwala, A., and Wong, W. 2006. Unifying CPM and linear scheduling: a definitive treatment, Joint 2006 CIB W065/W055/W086 International Symposium Proceedings for Construction in the XXI century: Local and Global Challenges, 18-30, Rome, Italy, 12 pages.

Shaaban, S., Lockley, S., and Elkadi. H. 2001. Information visualization for the architectural practice. Proceedings of the IEEE Fifth International Conference on Information Visualization, London, pp. 43-50.

Shneiderman, B. 1996. The eyes have it: A task by data type taxonomy for information visualization. Proceedings of the IEEE Symposium on Visual Languages. IEEE Computer Society, Los Alamitos, Washington, D. C., pp. 336-343.

Songer, A. D., Hays, B., and North, C. 2004. Multidimensional visualization of project control data. Construction Innovation 2004; 4: pp. 173-190.

Spence, R. 2000. Information visualization. ACM Press, New York.

Staub, S. and Fischer, M. 1998. Constructability reasoning based on a 4D facility model. Structural Engineering World Wide, T191-1 (CD ROM Proceedings), Elsevier Science Ltd.

Thomas, J. J., and Cook, K. A. 2005. Illuminating the path: The research and development agenda for visual Analytics." 1 200.

Tufte, E. R. 1983. The visual display of quantitative information. Cheshire CT: Graphic Press

Tversky, B., Morrison, J. B., and Batrancourt, M. 2002. Animation: can it facilitate. International Journal of Human-Computer Studies, Academic Press Inc., Duluth, Minnesota, 57:247-262..

Vanhoucke, M. 2006. Work continuity constraints in project scheduling. Journal of Construction Engineering and Management, Vol. 132, No. 1, pp. 14-25.

Zhang, P. and Zhu, D. 1997. Information visualization in project management and scheduling. Proceedings of the fourth International Conference on Decision Support Systems, ISDSS' 97, Lausanne, Switzerland.

3 CONCLUSIONS AND RECOMMENDATIONS

3.1 SUMMARY

Very large sets of multi-source, multi-dimensional and time varying data are generated during the execution of construction projects, especially large-scale infrastructure projects. Emphasized in this thesis is how data visualization can provide important insights during the planning, implementation and post project analysis phases of linear projects in an urban environment, which are attended by a complex working environment and multiple stakeholders. These insights can lead to enhanced communication and better decision making.

Thesis objectives are four fold: (i) examine how the representation of a schedule using linear planning charts can assist with assessing the quality of a schedule in terms of the construction strategy, communicate schedule intent to projects participants, and assist with telling the as-built story; (ii) explore images useful for representing multi source, multi-dimensional, time varying as-built construction data in support of management functions specifically with regards to communication and decision making; (iii) demonstrate the ability of visual representations of construction data to assist in telling the as-built story of a project in a manner that provides useful insights to project participants; and, (iv) critique the images presented in light of the data visualization principles and interaction tools identified, and suggest improvements as appropriate and possibly other images, including properties desired.

In addressing these objectives, the methodology involved a review of computer science and construction literature as it pertains to data visualization and a case study of a past project which reflected the scale and complexity of planning and executing linear projects in an urban environment. The planned and as-built story were captured from the available data depicting the contractor's perspective in the project's product, process, and as-built views which were replicated in a research software system called REPCON software. This system supports selected data visualization capabilities, which were examined and critiqued as part of this thesis.

It is demonstrated that data visualization is a powerful paradigm for gaining insights into the quality of a project's plan and for understanding a project's as-built performance. Greater benefits could be achieved by exploiting cutting edge visualization tools and by designing and implementing a more comprehensive set of images.

3.2 CONCLUSIONS AND CONTRIBUTIONS

The construction industry is confronted with challenges related to handling and representing multi-dimensional, multi-source and time varying data in support of management functions relating to planning, organizing, directing/leading and controlling for the project phases of pre-construction, execution, and post-project analysis. Demonstrated in this thesis is the ability to visualize heterogeneous construction data in an effective and efficient manner employing visual analytic and interactive techniques. A key virtue of the images examined is the ability to represent in compact form vast volumes of data in a way that assist management to gain insights and improve decision making and communication amongst project participants. Specifically, it was concluded that the ability to portray schedule data in a linear planning chart as well as other schedule representations combined with pictorial representations of the construction corridor and methods to be used, when embedded in an interactive environment can assist greatly with the task of assessing the quality of construction schedule/plans in terms of the construction strategy as well as capturing as-built story of the control phase of the project execution while addressing issues of scalability and complexity of data.

Further, it was demonstrated that data visualization is a powerful paradigm in capturing and telling a project's as-built story from various perspectives, including working conditions encountered and distribution of problems in time and space. Finally, by critiquing the various images presented, it has been concluded these images have numerous strengths, there is a need to improve its human computer interactive capabilities, and in particular, to take advantage of the latest state-of-the-art technologies.

3.3 RECOMMENDATIONS FOR FUTURE RESEARCH WORK

Future work will be directed at designing visual images for a broader range of construction data and management functions (e.g. as-built data in the form of change orders, request for information (RFI's), photos, etc.), at enhancing the human computer interaction components (such as highlight and overlay, linked data views), exploiting latest state-of-the-art tools for data visualization (such as future versions of ChartFX), and creating composite images with linked views (such as linking bar and LP chart and their association with photos and environmental data), in order to explore the benefits of a more holistic visualization environment.

3.4 REFERENCES

Ahlberg, C. and Shneiderman, B. 1994. Visual information seeking: Tight coupling of dynamic query filters and start-field displays. Proceedings of CHI, ACM Press Boston, pp. 313-317.

Baskinger, M. and Nam, K. C. 2006. Visual narratives: the essential role of imagination in the visualization process. ACM International Conference Proceeding Series Vol. 243. Proceedings of the Asia Pacific Symposium on Information Visualization. Vol. 6, pp. 217-220

Beermann, D., Munzner, T., and Humphreys, G. 2005. Scalable, robust visualization of very large trees. Proceeding of EuroVis 2005, IEEE VGTC Symposium on Visualization, pp. 1-8.

Bertin, J. 1983. Semiology of graphics. Madison, WI: University of Wisconsin Press.

Card, S. K., Mackinlay, J. D., and Shneiderman, B. 1999. Readings in information visualization: Using vision to think. Morgan Kaufmann Series in Interactive Technologies, Morgan Kaufmann publisher.

Chiu, C., and Russell, A. D. 2007. Construction process data plus visualization tools equals performance insights. ASCE Construction Research Congress, Academic Event Planners, LLC, USA.

Dzeng, R. J.; Tserng, H. P.; and Wang, W. C. 2005. Automating schedule review for expressway construction. Journal of Construction Engineering and Management, Volume 131, Issue No. 1, pp. 127-136.

El-Rayes, K. 2001. Object-oriented model for repetitive construction scheduling. Journal of Construction Engineering and Management, Vol. 127, No. 3, pp. 199-205.

El-Rayes, K. and Moselhi. O. 1998. Resource-driven scheduling for repetitive activities. Construction Management and Economics, Vol. 16, No. 4, pp. 433-446(14).

Environment Canada Web Site for past environmental/weather data http://www.climate.weatheroffice.ec.gc.ca/advanceSearch/searchHistoricDataStations

Hegazy, T., Elhakeem, A., and Elbeltagi, E. 2004. Distributed scheduling model for infrastructure networks. Journal of Construction Engineering and Management. Vol. 130, Issue No. 2, pp. 160-167.

Hyari, K. and El-Rayes. K. 2006. Optimal planning and scheduling for repetitive construction projects. Journal of Management in Engineering, Vol. 22, No. 1, pp. 11-19.

Keim, D. A. 1996. Databases and visualization. Proceedings of the ACM SIGMOD International Conference on Management of data, Montreal, Quebec, Canada.

Korde, T., Wang, Y., and Russell, A. D. 2005. Visualization of construction data. 6th Construction Specialty Conference, Toronto, Ontario, Canada. CT-148-1 to CT-148-11.

Liston, K., Fischer, M., and Kunz, J. 2000. Designing and evaluating visualization techniques for construction planning. Computing in Civil and Building Engineering, pp. 1293-1300.

Nielsen, Y. and Erdogan, B. 2007. Level of visualization support for project communication in the Turkish construction industry: A quality function deployment approach. Canadian Journal of Civil Engineering. 34: pp. 19-36.

Norman, D. A. 1993. Things that make us smart. Defending human attributes in the age of the machine. Perseus Books, New York.

Pilgrim, M., Bouchlaghem, D., Loveday, D., and Holmes, M. 2000. Abstract data visualization in the built environment. Proceedings of IEEE International Conference on Information Visualization, London, pp. 126-134.

Qin, Q., Zhou, C., and Pie, T. 2003. Taxonomy of visualization techniques and systems – Concerns between users and developers are different. The State Key Lab of Resources and Environmental Information System, Institute of Geographic Science and Resources Research, Chinese Academy of Sciences, Beijing, China.

Russell, A. D. and Udaipurwala, A. 2000. Assessing the quality of a construction schedule. Proc., of the ASCE Construction Congress VI, Orlando, Florida, USA, 928-937.

Russell, A. D. and Udaipurwala, A. 2002. Construction schedule visualization. Proceedings of the International Workshop on Information Technology in Civil Engineering, Washington D. C., USA, pp. 167-178.

Russell, A. D. and Udaipurwala, A. 2004. Using multiple views to model construction. CIB World Building Congress, Toronto, Canada. 11 pages.

Russell, A. D. and Wong, W. C. M. 1993. A new generation of planning structures, Journal of Construction Engineering and Management, ASCE, Vol. 119, Issue No. 2, pp. 196-214.

Russell, A. D., Udaipurwala, A., and Wong, W. 2006. Unifying CPM and linear scheduling: a definitive treatment, Joint 2006 CIB W065/W055/W086 International Symposium Proceedings for Construction in the XXI century: Local and Global Challenges, 18-30, Rome, Italy, 12 pages.

Shaaban, S., Lockley, S., and Elkadi. H. 2001. Information visualization for the architectural practice. Proceedings of the IEEE Fifth International Conference on Information Visualization, London, pp. 43-50.

Shneiderman, B. 1996. The eyes have it: A task by data type taxonomy for information visualization. Proceedings of the IEEE Symposium on Visual Languages. IEEE Computer Society, Los Alamitos, Washington, D. C., pp. 336-343.

Songer, A. D., Hays, B., and North, C. 2004. Multidimensional visualization of project control data. Construction Innovation 2004; 4: pp. 173-190.

Spence, R. 2000. Information visualization. ACM Press, New York.

Staub, S. and Fischer, M. 1998. Constructability reasoning based on a 4D facility model. Structural Engineering World Wide, T191-1 (CD ROM Proceedings), Elsevier Science Ltd.

Thomas, J. J., and Cook, K. A. 2005. Illuminating the path: The research and development agenda for visual Analytics." 1 200.

Tufte, E. R. 1983. The visual display of quantitative information. Cheshire CT: Graphic Press

Tversky, B., Morrison, J. B., and Batrancourt, M. 2002. Animation: can it facilitate. International Journal of Human-Computer Studies, Academic Press Inc., Duluth, Minnesota, 57:247-262..

Vanhoucke, M. 2006. Work continuity constraints in project scheduling. Journal of Construction Engineering and Management, Vol. 132, No. 1, pp. 14-25.

Zhang, P. and Zhu, D. 1997. Information visualization in project management and scheduling. Proceedings of the fourth International Conference on Decision Support Systems, ISDSS' 97, Lausanne, Switzerland.